**Naval Surface Warfare Center**
**Carderock Division**
West Bethesda, MD 20817-5700

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Total Ship Systems Directorate

Technical Report

# Logistics Enabler for Distributed Forces

by

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A Center for Innovation in Ship Design study was conducted to investigate an Advanced Logistics Delivery System. ALDS is an advanced sea-based concept capable of providing rapid logistic sustainment from a ship at sea directly to dispersed military forces maneuvering ashore. The system consists of a shipboard mechanical launcher and an autonomous, unmanned glider designed to transport cargo. This study focused on the aerodynamic design of a flying wing ALDS glider utilizing inflatable wing technology. Predicted performance estimates were made for the mechanically launched vehicle. Extended range capabilities using booster rockets were also explored.

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# Nomenclature

| | |
|---|---|
| $C_L$ | Coefficient of lift (3D) |
| $C_l$ | Coefficient of lift (2D) |
| $C_D$ | Coefficient of drag (3D) |
| $C_d$ | Coefficient of drag (2D) |
| $C_{D0}$ | Zero lift drag |
| $C_M$ | Coefficient of moment |
| $C_{Mcg}$ | Coefficient of moment (about center of gravity) |
| $C_{Mw}$ | Mean moment coefficient of wing about center of gravity |
| $C_{M0}$ | Airfoil moment coefficient about quarter chord point |
| $\alpha$ | Angle of attack (radians) |
| $\alpha_0$ | Zero lift angle of attack (radians) |
| $x_{cg}$ | Location of center of gravity from nose (feet) |
| $x_{ac}$ | Location of aerodynamic center from nose (feet) |
| $R_e$ | Reynold's number |
| $\sigma$ | Static margin |
| A | Aspect ratio |
| e | Oswald's efficiency |
| LIM | Linear induction motor |

# 1 Introduction

The Advanced Logistics Delivery System (ALDS) is an advanced sea-based concept capable of providing rapid sustainment of goods and supply to dispersed military forces maneuvering ashore. The system consists of a shipboard mechanical launcher and an autonomous, unmanned glider designed to transport cargo such as food, ammunition, fuel and water. The glider is accelerated to high speed by the launcher. During its steep ascent, the kinetic energy provided to the glider by the launcher is converted into potential energy until the glider reaches its maximum altitude. The vehicle then glides at relatively slow speed to the delivery point. Onboard avionics control and guide the glider throughout its flight. This report provides an overview of the ALDS concept, a description of an innovative flying wing design for the ALDS glider, an overview of the launch ship design and identifies capability gaps for the technology.

Two variants of the ALDS concept have been previously studied[1] at the Naval Surface Warfare Center, Carderock Division. The study focused on a catapult launched, fixed wing glider similar to recreational gliders and an air-dropped glider with inflatable wings. The study concluded that the catapult launched glider lacked sufficient range. Consequently, the preferred ALDS was determined to be an inflatable wing glider capable of launch via helicopter, fixed wing aircraft, or rocket at sufficient altitude to provide militarily useful range. Major limitations of such a concept are its dependence on high value manned aircraft, the operational complexity of handling and launching relatively large rockets at sea, and a relatively low cargo delivery rate.

A catapult based ALDS system has strong appeal for littoral operations. Modest advances in launcher technology, such as linear induction motors (LIM) similar to those currently under development for use as catapults on aircraft carriers, should allow development of ALDS launcher systems which are sufficiently compact for installation in shallow draft, intra-theater delivery ships displacing a few thousand tonnes. Furthermore, one of these systems should be capable of sustaining sufficiently high launch rates to provide direct ship to maneuvering unit supply rates of about 15 short tons per hour. This piece of ships equipment should be more reliable than manned aircraft and require less manpower, maintenance and fuel.

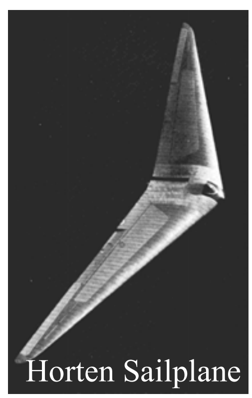
Notional design requirements were adopted during the earlier ALDS study for major system parameters. A LIM launcher providing 30 g's acceleration and a 500 kt launch speed was selected to provide the necessary energy in a compact package suitable for installation in small ships. Such a system was expected to support a launch every two minutes. Cargo weight was set at 1,000 lbs with a minimum cargo volume of 30 $ft^3$ to house the types of wet and dry cargos required in packages suitable for small maneuver units. The launch rate and cargo rate equate to a sustained delivery rate of 15 short tons per hour. Although not addressed explicitly, cost was to be kept sufficiently low as to allow the gliders to be considered expendable if tactically desirable. These requirements were retained for the current study.

The current study re-examined the catapult launched ALDS concept by developing an advanced flying wing glider incorporating inflatable wings and exploring the effects of variation in launch angle on the trajectory and range of the glider. The inflatable wings are deployed at apogee to enhance aerodynamic efficiency during the relatively slow glide to the delivery site.

The ALDS vehicle presented is a flying wing glider with two modes of operation. It is composed of a central launch body with inflatable wing pods attached. The centerbody of the flying wing is sized to enclose the cargo, house necessary avionics, and mount inflatable wing pods on either side. The glider remains in this configuration during launch and climb-out to minimize drag and energy loss. Centerbody shape and control systems provide necessary stability and control during the ascent phase. Following launch from a ship's deck, the centerbody then climbs at an angle of about $30^{o}$ until the aerofoil approaches stall at the apogee. The compact centerbody provides the minimal lift required during ascent while producing minimum drag.

At apogee, the wings inflate and the ALDS vehicle glides to its target. During the glide phase, the vehicle is effectively a high performance glider similar to recreational gliders designed and built by the German Horton brothers in the 1930's. These sailplanes have demonstrated very high aerodynamic gliding efficiency with lift to drag ratios over 40. However, if the wings were inflated during the high-speed launch/climb phase, the aerodynamic forces induced on launch would severely limit the height attainable due to the resulting drag. Also, at launch speeds of 500 kts, the wing structure would be required to withstand the associated large forces, making them heavier, thereby reducing payload. The launch body is therefore a small flying wing encasing the payload and avionics, capable of generating lift in the climb with relatively low drag.


Northrop N1-M


Horten Sailplane


Northrop B-2

American powered flying wing pioneer Jack Northrop concluded[2] that the drag of a flying wing was 50% that of a conventional aircraft, and projected future improvement to 40%. His belief in the merits of flying wings sustained development of the concept from his first successful aircraft the N1-M in 1940 through the modern B-2 bomber. Consequently, flying wings appeared to be an ideal choice for a glider where a high lift to drag ratio is required.

The study also examined the design and operation of a suitable launch ship. A trimaran was selected as most suitable for this application. Due to volume requirements, the ALDS glider requires onboard manufacture or assembly. Both options were examined and a near term assembly process identified. Cargo handling techniques were also assessed.

# 2 ALDS Glider Design

## 2.1 Flying Wing

There is much controversy over whether flying wings are advantageous[2]. The lack of such designs in production may suggest they are inferior over conventional tailed aircraft. The reality is that flying wings are only suitable for certain applications. A small unmanned, un-powered glider is one such application.

Flying wings generally have reduced drag, due to the lack of a tail and an integrated fuselage. However, a lower drag coefficient can only be attained through the correct design of the wing. It can be a complex procedure to stabilize and trim a flying wing, while at the same time maintaining a low-drag lift distribution. Due to the lack of a tail to aid in trim, the center of gravity limits are much smaller for a flying wing. Also, it is often a challenge to locate passengers inside of the wing shape. However, with ALDS, there are no passengers to house, no engine to be fitted and the load variation (i.e. center of gravity variation) is small. Therefore, a flying wing is ideal for such a low speed, simple design aiming to maximize range.

The ALDS glider is to be assembled onboard the ship. Flying wings have less structure than their tailed equivalents, resulting in reduced storage space requirements and easier assembly. Also, less structure results in lower manufacturing costs which is advantageous for an expendable design.

## 2.2 Initial Sizing

The most important performance characteristic in the ALDS glider design is the lift to drag ratio (L/D). This value is also equal to the glide slope, e.g. a lift to drag ratio of ten means the aircraft will glide ten miles for every mile descended. This characteristic is important due to the lack of an engine in the ALDS design. There are therefore only two ways to maximize range of such an aircraft: increase the apogee height or increase the glide slope.

Standard sailplanes achieve a lift to drag ratio of around 25, while high performance sailplanes can achieve values of up to 40. There have been examples of sailplanes with lift to drag ratios in excess of 60. However, sailplanes generally only carry the payload of the pilot, whereas ALDS is expected to carry at least 1,000 lbs. This means the long, slender wings have to carry a greater load than on a conventional sailplane, i.e. a higher wing loading. Also, the bending moment at the root increases. Therefore a target lift to drag value of 30 was chosen. This is a realistic value and represents a balance between feasibility and desired range.

One of the main influences on the lift to drag value is aspect ratio, i.e. the ratio of wingspan to the average chord. As aspect ratio increases, cross flow decreases and the flow over the wing becomes more two dimensional, reducing the induced drag. High aspect ratio alone is not enough to ensure a high lift to drag ratio, correct flow must also

be maintained over the wing. Using historical trends, an aspect ratio of 20 was chosen for the ALDS glider design.

Wing loading was assumed to be 6.1 lb/ft$^2$. This value was selected from historical sailplane trends, but also by investigating inflatable wing technology. From this a wing area of 244 ft$^2$ and a wingspan of 70 ft were calculated.

Most textbooks suggest taper ratios, ratio of tip chord to root chord, of 0.25 to 0.3 are more conductive to low induced drag. However, this is not the case for flying wings and sources suggest a high taper ratio for stability reasons. Therefore, a taper ratio of 0.75 was chosen.

Generally, sweep is limited for aircraft operating close to Mach 1, as it reduces the normal component of velocity over the wing. Using sweep for low speed aircraft reduces the lift. However, as will be examined later, sweep is required for flying wings to maintain stability. Therefore an initial sweep value of 20$^o$ was chosen, based on historical designs.

The centerbody (Figure 1) was sized mainly around the cargo requirements. It is a very low aspect ratio (1.13) flying wing with a 9.8 ft wingspan that houses the cargo and the avionics. Attached to the sides are the wing pods that inflate at apogee. The root chord of 14.8 ft tapers to 8.7 ft at the tip.  The cargo bay is sized to carry 1,000 lbs of mixed cargo (fuel, water, dry cargo) packed into a cargo bay occupying a total volume of 30 ft$^3$.

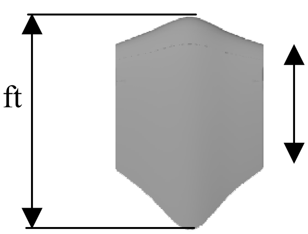


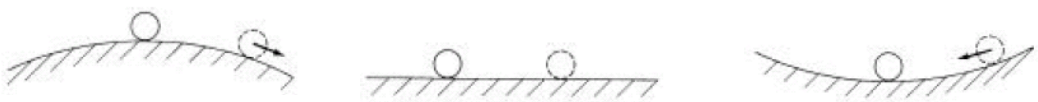

**Figure 1 Centerbody Profile**

## 2.3 Stability and Trim

The main concern with flying wings is that they are generally unstable due to the lack of a tail. Much controversy surrounds the methods used to successfully design a flying wing and different sources will site pros and cons for each.

For steady flight, the forces acting on an aircraft must be in balance. Therefore, there must be no resultant turning moment about any center of gravity axis. When this is achieved, the aircraft is said to be trimmed. An aircraft is said to be statically stable if it tends to return to its initial flight conditions after being disturbed by a gust or a small impulsive control input. Normally, for steady level flight, the aircraft is required to be both trimmed and stable.

There is considerable confusion between trim and stability, and this is evident in a large number of texts relating to flying wings. For example, a ball balanced on top of a hill is balanced or trimmed, but certainly not stable (Figure 2).



Statically unstable
*Negative static stability*

*Neutral static stability*

Statically stable
*Positive static stability*

**Figure 2 Stability Definitions**

The aerospace community is inexperienced with flying wings when compared to tailed designs. A lot of research has been performed with tailed aircraft and as a result there are a lot of documented theoretical and empirical methods for such designs. With flying wings this research does not exist and a lot of the design is done through experimentation. Even the Horten brothers, who designed many successful tailless aircraft, failed to document much of their work. Consequently, a 'one and only' design method for flying wings does not exist. For example, the initial ALDS technical paper[3] made reference to the use of the Bell distribution to achieve stability. Further research has revealed this to be a very inefficient method of designing the aircraft and its claimed ability to eliminate adverse-yaw problems was inaccurate[2].

A new method to design the flying wing was developed through a combination of selected sources and new innovation.

### *2.3.1 Longitudinal Static Stability*

The condition for longitudinal static stability is that the aircraft will produce a nose down moment about the center of gravity ($C_{Mcg}$) when the angle of attack increases, thus restoring the aircraft to equilibrium. By definition a nose-down moment is negative. The change in $C_{Mcg}$ with respect to angle of attack can be defined as :

$$\Delta C_{M_{cg}} = \frac{\delta C_{Mcg}}{\delta \alpha}\alpha \qquad (0.1)$$

For stability this implies that the rate of change of moment about the center of gravity with respect to the angle of attack $\left(\delta C_{M_{cg}} / \delta \alpha\right)$ must be negative, i.e. increasing the angle of attack results in a nose-down moment :

$$\frac{\delta C_{Mcg}}{\delta \alpha} < 0 \qquad (0.2)$$

Graphically, this implies that the gradient of the moment-lift slope must be negative (Figure 3).

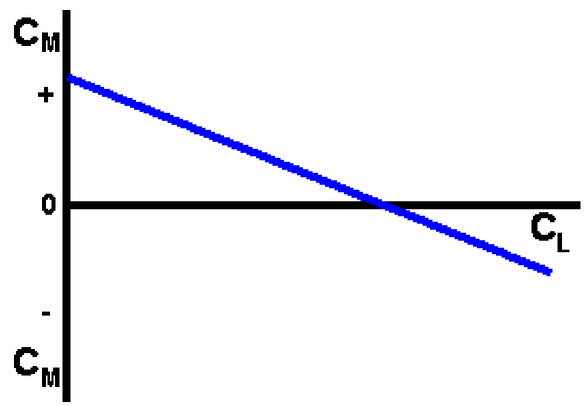



**Figure 3 Coefficient of Pitching Moment vs. Coefficient of Lift for Aircraft with Longitudinal Static Stability**

From a practical point of view, this is achieved by placing the center of gravity forward of the aerodynamic center. The center of gravity ($x_{cg}$) is the point about which rotations occur and the aerodynamic center ($x_{ac}$) is the point on the wing about which all changes in lift effectively act.

Examine first the situation where the center of gravity is placed behind the aerodynamic center (Figure 4). When the airfoil pitches up the lift is increased, and this lift creates a nose up moment about the center of gravity making the airfoil diverge from its equilibrium position. This is a statically unstable situation.

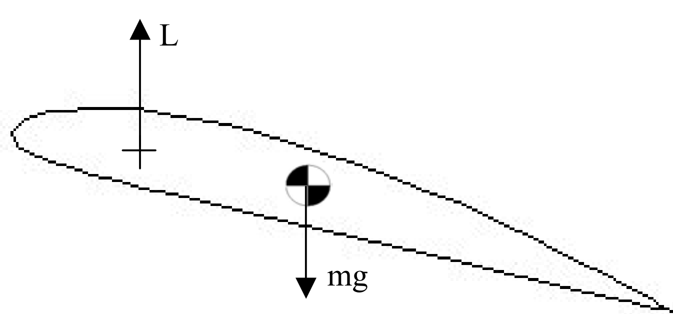



**Figure 4 Airfoil with Center of Gravity behind Aerodynamic Center**

When the center of gravity is ahead of the aerodynamic center (Figure 5), a nose up disturbance increases lift, but this creates a nose down moment returning the airfoil to its original state. This is a statically stable situation.

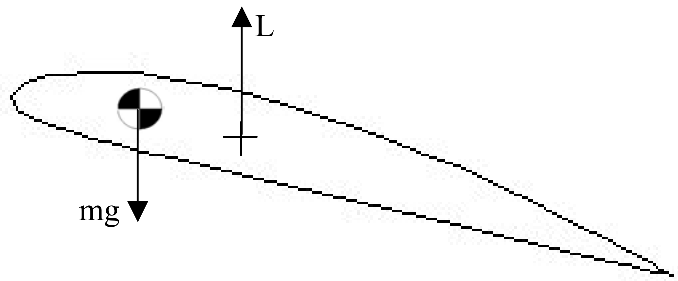



**Figure 5 Airfoil with Center of Gravity ahead of Aerodynamic Center**

There is very little that can be done on the ALDS glider to move the center of gravity. The cargo is located at a set location (thickest section of the wing) and the wing location cannot be moved (as with conventional tailed aircraft) due to the flying wing design. Therefore, the wing sweep must be modified to move the aerodynamic center to a suitable location.

The distance between the aerodynamic center and the center of gravity determines the amount of stability. If the center of gravity is too close to the aerodynamic center, the returning moment is small and the wing returns too slowly to equilibrium, creating a 'sluggish' response. If the center of gravity is too far away from the aerodynamic center the wing returns too quickly to the equilibrium position and may result in dynamic instability (divergent oscillations). The static margin is defined as the distance between the aerodynamic center and the center of gravity, divided by the mean chord. Static margin is usually expressed as a percentage and the ALDS glider has a value of 5% at design point. This value was chosen at the recommendation of Walter Panknin[4], a well-known individual within the flying wing community.

A weight breakdown was performed on the ALDS glider to determine the center of gravity. A spreadsheet was then created to calculate the aerodynamic center and center of gravity with the leading edge sweep as a variable. A sweep of 15.6$^{o}$ led to the center of gravity located at 5.3 ft from the nose, and the aerodynamic center located at 5.5 ft from the nose. This provided the required 5% static margin.

Analysis was then performed to examine the payload limits. A 2% static margin corresponds to a 600 lb payload and an 8% margin to a 1,600 lb payload. These were considered the center of gravity (hence payload) limits.

If further analysis provides a more accurate breakdown than calculated in this study, the spreadsheet should be used to recalculate the required sweep. It is well known that flying

wings are extremely sensitive to aerodynamic center movements (due to lack of tail) and this was evident in the study.

### 2.3.2 Trim

Locating the center of gravity in front of the aerodynamic center is not a guarantee for equilibrium; it is only a requirement for longitudinal stability. For the ALDS glider to be in equilibrium, the sum of the moments about the center of gravity must be equal to zero. The position of the center of gravity was determined by stability requirements; therefore equilibrium can only be achieved by the appropriate airfoil and twist selection. On conventional tailed aircraft it is possible to adjust the difference between the angles of incidence of wing and tail plane during the first flight tests. Flying wings have a built in twist that cannot easily be adjusted like this. It is therefore very important to get the right combination of airfoil selection and twist before the aircraft is built. The calculation of these parameters is quite complex[2]. What follows is a simple, approximate approach that is suitable for the conceptual design. Should ALDS reach a preliminary design stage, reference 2 should be used to perform detailed calculations. The level of accuracy at this stage is not enough to justify performing such a complex analysis and the approximate approach gives satisfactory results.

### 2.3.3 Airfoil Selection

Several criteria were used in determining the correct airfoil selection:

- L/D max occurs at design $C_L$ (first approximation $C_L \approx 0.5$),
- $C_d \approx C_{D0}$ (for flying wing, $C_{D0} \approx 0.01$),
- $C_{M0}$ as close to zero as possible to make the aircraft easier to trim,
- Airfoil designed for intended Reynold's number (Re ≈ 2 million),
- Thickness to chord ratio ~ 15% (maximize lift in low speed flight, without encountering separation).

The NASA Laminar Flow NLF0215 airfoil (Figure 6) was originally selected for this design because the section shape was compatible with cargo stowage requirements and it has desirable aerodynamic properties[3].

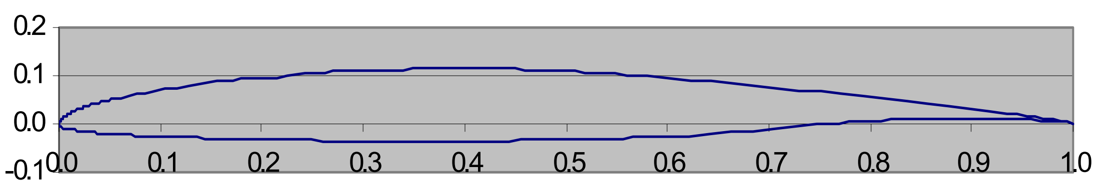



**Figure 6 NLF0215 Airfoil**

Further analysis revealed this airfoil had a moment coefficient equal to –0.165, which is relatively large. However, a large area was still required for the cargo stowage. Producing a trimmed aircraft using this section proved impossible without using a tail.

Aerodynamically, a symmetric airfoil such as NACA0018 would be most suitable due to its zero moment coefficient. However, the cross section is so large that a considerable amount of form drag is generated. Additionally, calculations using a vortex lattice panel method[5] showed that a symmetric airfoil was unable to generate the required lift in the climb. Therefore, the NACA1218 airfoil was selected for the centerbody. This airfoil allowed room for the cargo and generated the required lift in the climb, without having an excessively large moment coefficient. A slightly thinner NACA1211 was used for the centerbody root to reduce centerbody size and drag. Properties of the airfoils are shown in Table 1.

The moment about the center of gravity can be expressed in terms of the static margin, σ.

$$C_{M_{cg}} = -\sigma C_L + C_{Mw} \tag{0.3}$$

The required $C_{Mw}$ in trim is obtained by setting $C_{Mcg}$ to zero in Equation (0.3).

$$C_{Mw} = \sigma C_L \tag{0.4}$$

With $C_L$ equal to 0.500 and σ of 0.050, the overall moment required by the wing in flight, $C_{Mw}$, is equal to 0.025. Reflex camber airfoils with positive moment coefficients were used for the wing to counteract the centerbody airfoil selection as shown in Table 1.

| Location | Airfoil | $C_{M0}$ | $\alpha_0$ (deg) |
|---|---|---|---|
| Centerbody Root | NACA1211 | -0.0214 | -1.0 |
| Centerbody Tip | NACA1218 | -0.0214 | -1.0 |
| Wing Root | E182 | +0.0100 | -0.3 |
| Wing Tip | E184 | +0.0300 | +0.5 |

**Table 1 ALDS Airfoil Selection**

Large geometric twist angles can be used to stabilize wings with small sweep angles or highly cambered (large positive moment) airfoils. However, large geometric twist creates a large amount of drag when the wing is operated away from its design point. The geometric twist can be reduced by selecting different airfoils for the tip and root section of the wing. The difference between the zero lift lines is called aerodynamic twist and is used to improve the off design performance of the glider.

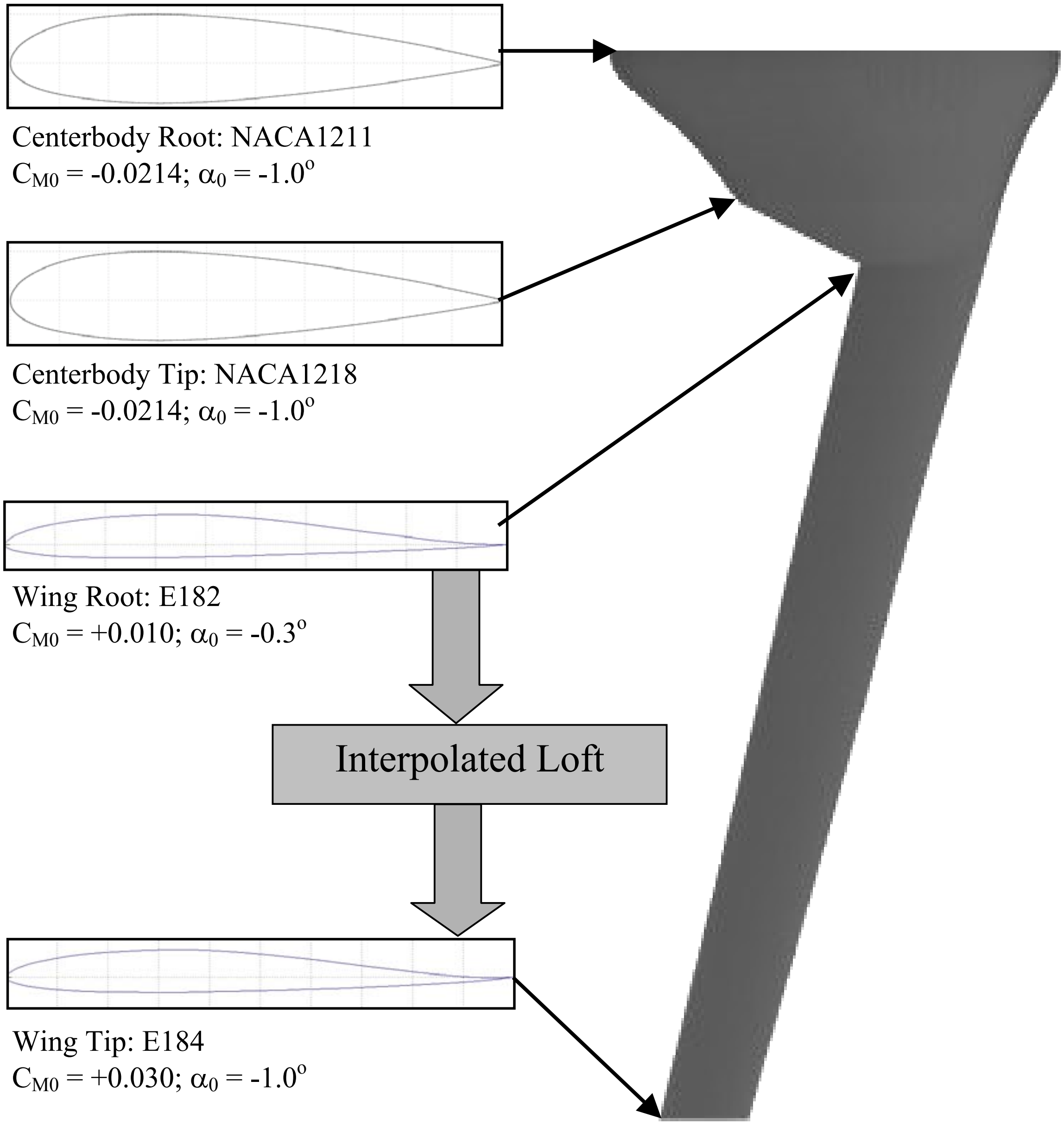



**Figure 7 ALDS Airfoil Selection**

### *2.3.4 Twist*

Using the above airfoils, the moment coefficient of the wing about the center of gravity, $C_{Mw}$, was found to have a value of 0.0142. This falls short of the required 0.025 and therefore twist must be used to trim the aircraft.

Sweep causes an upwash to be generated, increasing in strength towards the tip of the wing. This has the effect of increasing the local angle of attack outboard. Left unchecked this could cause the tips to stall, which is undesirable due to the loss of control.

Downwash is used to reduce the local angle of attack, also having the effect of making the inboard section stall first, which makes for an easier recovery.

Several methods exist to determine the required twist. There is also a debate whether linear twist should be used, or if the twist should be applied further outboard. Panknin provides a good overview of designing flying wings in his ‘Flying Rainbows’ lecture[4]. He talks about why sweep is needed and also comments that for small lift coefficients and high sweep (as in the case of the ALDS glider) very little twist is required. He presents the following formula for calculating the required twist.

$$\alpha_{total} = \frac{(K_1 \bullet C_{M root} + K_2 \bullet C_{M tip}) - \bar{C}_L \bullet St}{1.4 \bullet 10^{-5} \bullet \lambda^{1.43} \bullet \Upsilon}$$

$$\alpha_{geo} = \alpha_{total} - (\alpha_{L=0 root} - \alpha_{L=0 tip})$$

$b$ = wingspan
$t_{root}$ = root chord
$t_{tip}$ = tip chord
$\bar{t}$ = mean chord = $(t_{root} + t_{tip})/2$
$\lambda$ = aspect ratio = $b/\bar{t}$
$\Upsilon$ = angle of sweepback, as measured at 1/4 chord line
$\Gamma$ = taper ratio = $t_{tip}/t_{root}$
$K_1 = 1/4 \bullet (3 + 2\Gamma + \Gamma^2)/(1 + \Gamma + \Gamma^2)$
$K_2 = 1 - K_1$
$\alpha_{L=0root}$ = root section zero lift angle
$\alpha_{L=0tip}$ = tip section zero lift angle
$C_{Mroot}$ = moment coefficient of root section
$C_{Mtip}$ = moment coefficient of tip section
$\bar{C}_L$ = design lift coefficient
$St$ = stability factor (static margin)

**Figure 8 Panknin Twist Formula**

Panknin provides the formula without proof or reference, yet he claims to have made many successful designs by using it.

An alternate method is one by Dr. Martin Hepperle[5], who presents a simplified version of the method in reference 2. This method finds the required twist and then takes into account the airfoil selection, static margin, design lift coefficient and other aircraft parameters to calculate the geometric twist using a graphical method.

Both the Panknin and Hepperle method were used and the results were found to be almost identical. A downwash of –0.74$^{o}$ was calculated, representing a negative twist which, as previously explained, is desirable for the off-design performance. The low value of twist calculated is an indication of good airfoil selection. However, due to the upwash effect, the ALDS glider would stall first at the tip. This would be considered unacceptable in a manned glider, but is more acceptable for a fly-by-wire UAV, as efforts can be made to prevent stall. A downwash can be generated through different airfoil selection, but at the sacrifice of off-design performance.

Research indicates that the success of a flying wing design cannot be evaluated until it is actually flown. It is recommended that upon completion of preliminary design, the twist calculations be performed again before building an actual model. On the final iteration, it is recommended the detailed method of reference 2 be used to provide a better estimate of the required twist. However, as long as items such as wing weight remain only estimates, the lengthy calculation of reference 2 is not justified and the above approximations are sufficient.

## 2.4 Control Surfaces

It is essential that the launch body is adequately controlled during launch and climb-out. Controls are integrated into the V-shaped trailing edge of the body in the form of combined ailerons/elevators (Figure 9).

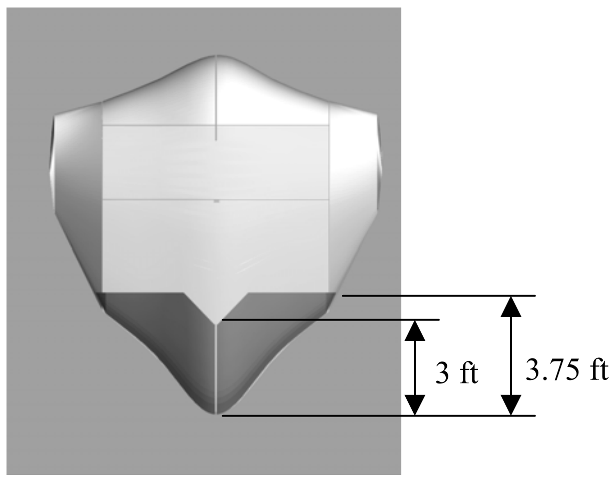



**Figure 9 Centerbody Control Surfaces**

These control surfaces were sized with consideration to conventional flap sizes, allowable space and control effectiveness. Typically, control surfaces occupy 15-25% of the wing chord. The ALDS centerbody is not a typical wing shape, but can be analyzed as low aspect ratio wing. Enough space was allocated in the centerbody for adequate control surface area and effectiveness. There are two control surfaces that meet at the centerline of the centerbody and collectively occupy approximately 19 $ft^2$, or 20% of the centerbody area.

Once the wings have inflated, controls on the launch body are a relatively inefficient way of controlling the ALDS glider. Large control deflections would be required resulting in high drag and energy losses. A more efficient approach is to locate control surfaces on the high aspect ratio inflated wing sections. An alternate approach is to provide control forces by warping the inflatable wing. Control using wing warping was demonstrated by the Wright Flyer in 1903. A series of cables with centerbody actuators could be used to distort the inflatable wing shape to provide necessary control forces. The controls on the launch body become secondary or backup controls if inflatable wing controls are developed.

## 2.5 Performance

### 2.5.1 Trajectory Analysis

A set of notional requirements was developed in order to design the ALDS vehicle. Key parameters such as payload, launch angle and launch mechanism were then varied to investigate their effect upon performance. In order to evaluate the effects and assess the trade-offs, a trajectory analysis was performed for the launch, climb and glide phases. It was assumed that in the climb, control would be applied such that ALDS maintains a constant climb angle. This is necessary to trim the centerbody as lift is generated in the climb.

***Equations of motion***

Forces on the free body diagram (Figure 10) of the ALDS glider in the climb were resolved parallel and perpendicular to the direction of travel, Equations (0.5). It was assumed that the centerbody generates enough lift to keep the body in equilibrium perpendicular to the direction of travel and that control is applied such that the angle of travel, α, remains constant.

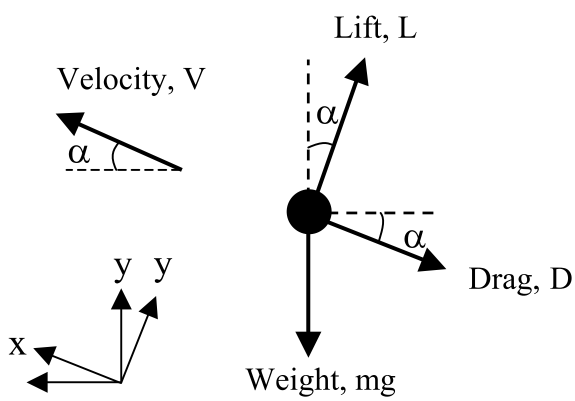



**Figure 10 ALDS Free Body Diagram**

$$
\begin{aligned}
&L - mg\cos\left(\overline{\alpha}\right) = 0 \\
&-D - mg\sin\left(\overline{\alpha}\right) = m\frac{d^2x'}{dt^2} \\
&\overline{\alpha} = \text{launch angle}
\end{aligned}
\tag{0.5}
$$

The ALDS glider is an aerodynamic body that generates lift and drag forces in the climb, Equations (0.6), and therefore cannot be treated as a simple projectile.

$$C_L = \frac{L}{\frac{1}{2}\rho V^2 S} = \frac{mg\cos\left(\overline{\alpha}\right)}{\frac{1}{2}\rho V^2 S}$$
$$C_D = \frac{D}{\frac{1}{2}\rho V^2 S} = C_{D0} + \frac{C_L^{\ 2}}{\pi Ae} \tag{0.6}$$

Substituting the aerodynamic equations, Equations (0.6), into the resolved forces equations, Equations (0.5), yields the equations of motion, Equations (0.7).

$$\frac{d^2x'}{dt^2} = \frac{-mg^2\cos^2\left(\overline{\alpha}\right)}{\frac{1}{2}\rho\left(\frac{dx'}{dt}\right)^2 S\pi Ae} - g\sin\left(\overline{\alpha}\right) - \frac{\rho\left(\frac{dx'}{dt}\right)^2 SC_{D0}}{2m}$$
$$\frac{dy'}{dt} = 0 \tag{0.7}$$
$$x = x'\cos\left(\overline{\alpha}\right)$$
$$y = y'\sin\left(\overline{\alpha}\right)$$

The second-order differential equation could not be solved analytically. MATLAB was used to solve the equations at varying launch angles using numerical methods. Energy losses were also calculated.

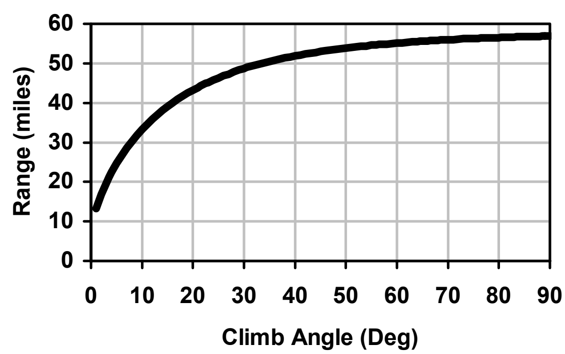



**Figure 11 Variation of Range with Climb Angle**

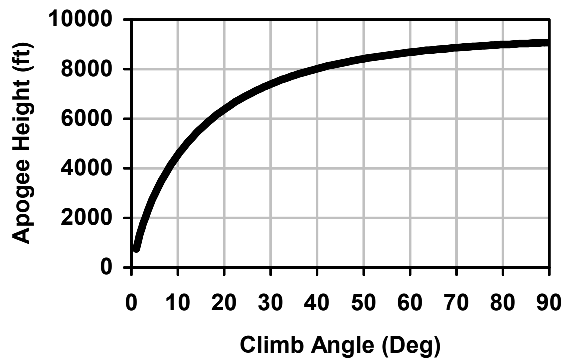



**Figure 12 Variation of Apogee Height with Climb Angle**

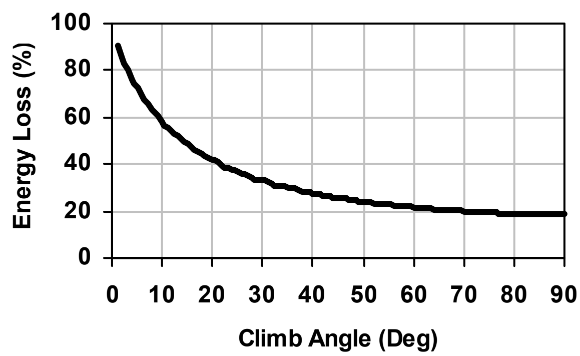



**Figure 13 Variation of Energy Loss with Climb Angle**

It was found that increases in climb angle resulted in increased apogee (Figure 12) and range (Figure 11). This means the glide phase is more effective than the climb in gaining range, which is expected given the large lift to drag ratio of the ALDS glider. Overall range is therefore controlled by the height achieved in the climb (assuming constant L/D).

To achieve the desired range of 50 miles, analysis showed a climb angle of $33^o$ is required (Figure 11). The analysis also showed that large energy losses occur if the ALDS centerbody must undergo a large rotation after leaving the deck of the ship. Consequently, the launch ship should launch the ALDS vehicle at this angle to avoid rotation in the climb. The $33^o$ launch attains an apogee height of 7,600 ft (Figure 12), with a 31% energy loss (Figure 13) in overcoming the drag of the ALDS vehicle.

Slight increases in range are possible with higher launch/climb angles. The range of the ALDS glider asymptotes to 58 mi as the climb angle tends to $90^o$. Hence, increasing the launch angle above $33^o$ makes little difference to the overall range. Furthermore, the practicality of installing such launchers onboard a ship becomes problematic.

ALDS was designed for a basic range of 50 mi carrying a payload of 1,000 lbs. It is possible to operate the glider in different configurations to carry greater payload and/or achieve a greater range.

The glider is capable of carrying a larger payload due to the low wing loading. To maintain the maximum glide ratio, the lift coefficient is kept constant. Glide speed is therefore varied with payload. When ship launched, it was assumed that the ALDS glider would be subject to a constant force that the LIM can provide. Therefore a variation in payload results in a modified launch velocity.

The main variable in determining range (assuming fixed L/D) is the height attained in the climb. Small, disposable rockets could be attached to the ALDS glider, which would fire in the climb augmenting the height gained. These rockets are relatively cheap and would not add to the mass of the glider in the glide phase. The rockets would be fired following launch from the deck and provide enough thrust to overcome the drag and the component of weight resolved in the direction of travel. The ALDS glider would therefore maintain a constant climb velocity until the rocket thrust expired.

The rockets would add considerable drag to the body. This is why the optimum performance would result from firing them immediately upon launch. The rockets can provide useful thrust and then be discarded so they do not contribute to the overall drag for the remainder of the climb.

Rocket data was examined (Figure 14) and the equations were extrapolated and included in the MATLAB trajectory analysis program.

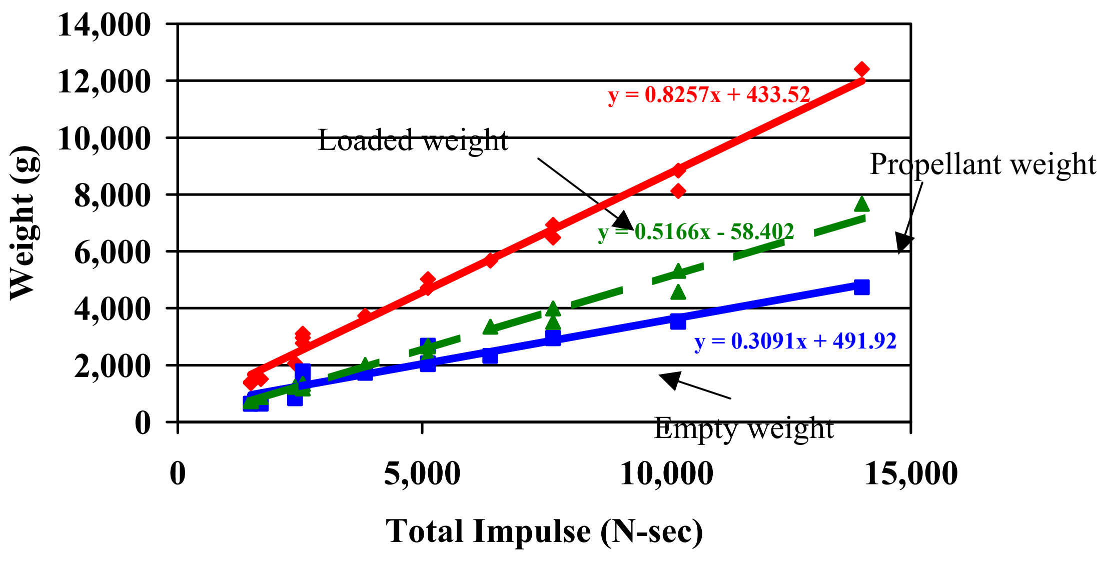



**Figure 14 Disposable Rocket Data**

The trajectory analysis program was used to calculate the performance of the ALDS glider with varying payload in the following configurations:

1. Basic ALDS configuration, ship launched.
2. ALDS plus rockets (100 lb, 200 lb, 550 lb)

The performance results are summarized in a range-payload plot (Figure 15).

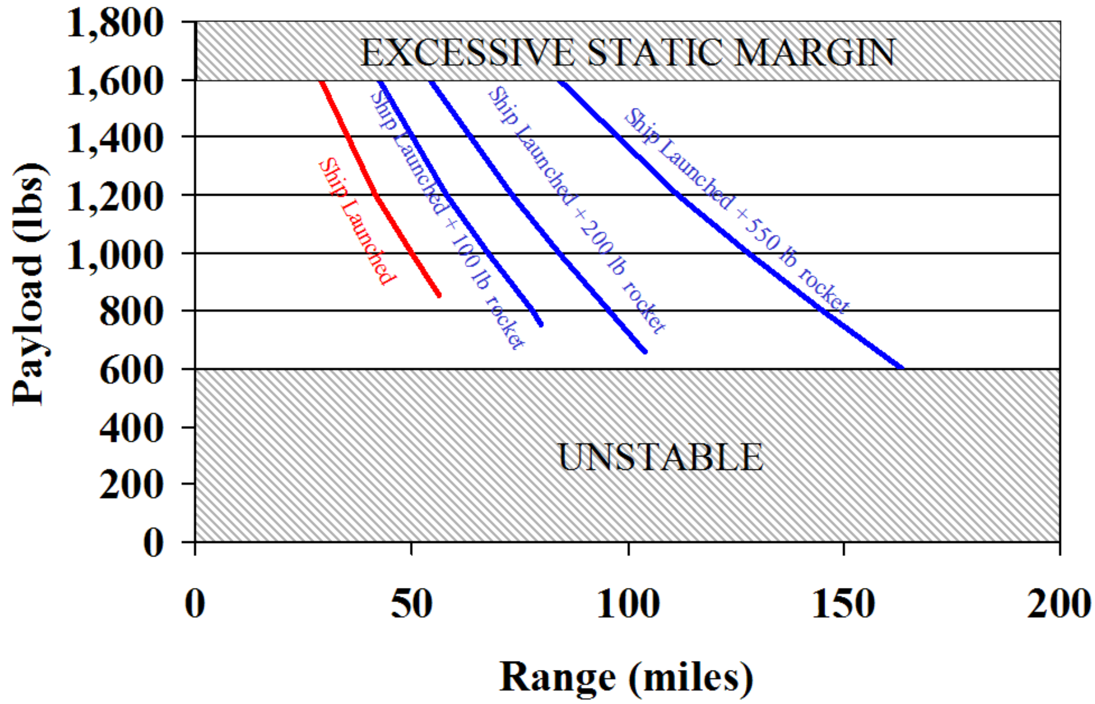



**Figure 15 Flying Wing ALDS Performance**

Increasing payload decreases the range achievable. The main reason for this is the limitation of the LIM launcher. The launcher was assumed to provide constant impulse. As the payload increases the launch velocity decreases, hence there is less kinetic energy to be converted into potential energy. However, a glider overloaded with 50% more than the design cargo would have a range of over 30 mi. Such a capability would allow a significant reduction in the number of gliders needed to supply forces at this shorter distance.

The addition of rockets produces a series of almost parallel lines with significant results. With limited payload and the addition of 550 lbs of rockets, a range of around 160 mi is achievable.

Alternately, the ALDS vehicle could be air-dropped from fixed wing aircraft at altitudes greater than the mechanical launch apogee to enhance range. For example, an ALDS vehicle launched at 35,000 ft would extend the reach of ALDS to around 200 mi from the drop point. This capability may be attractive for delivery of small amounts of high value cargo such as that needed to support remote Special Forces teams.

### *2.5.2 Climb Analysis*

The ALDS centerbody is required to generate lift in the climb (~5.6 kN). A vortex lattice panel method[6] was used to perform an aerodynamic analysis of the body with variations in speed and angle of attack. Combining this aerodynamic analysis (Figure 16) with the trajectory analysis, the variation of required angle of attack with velocity in the climb can be found (Figure 17).

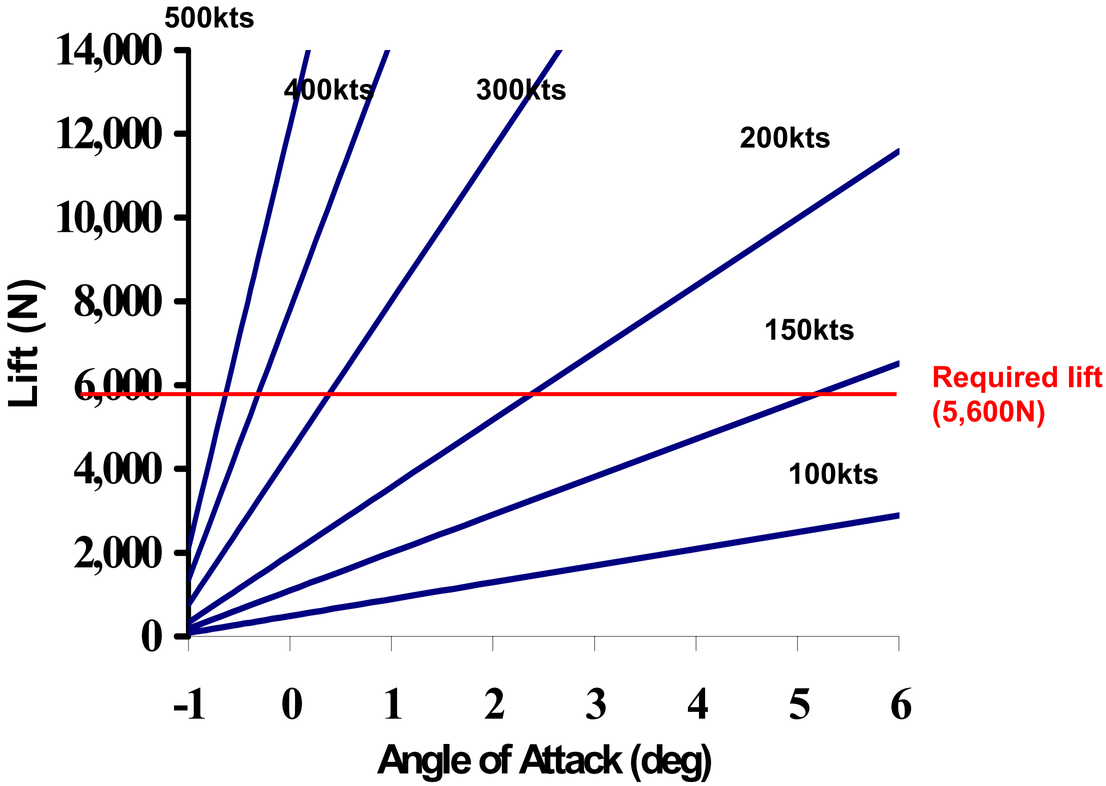



**Figure 16 Centerbody Climb Analysis**

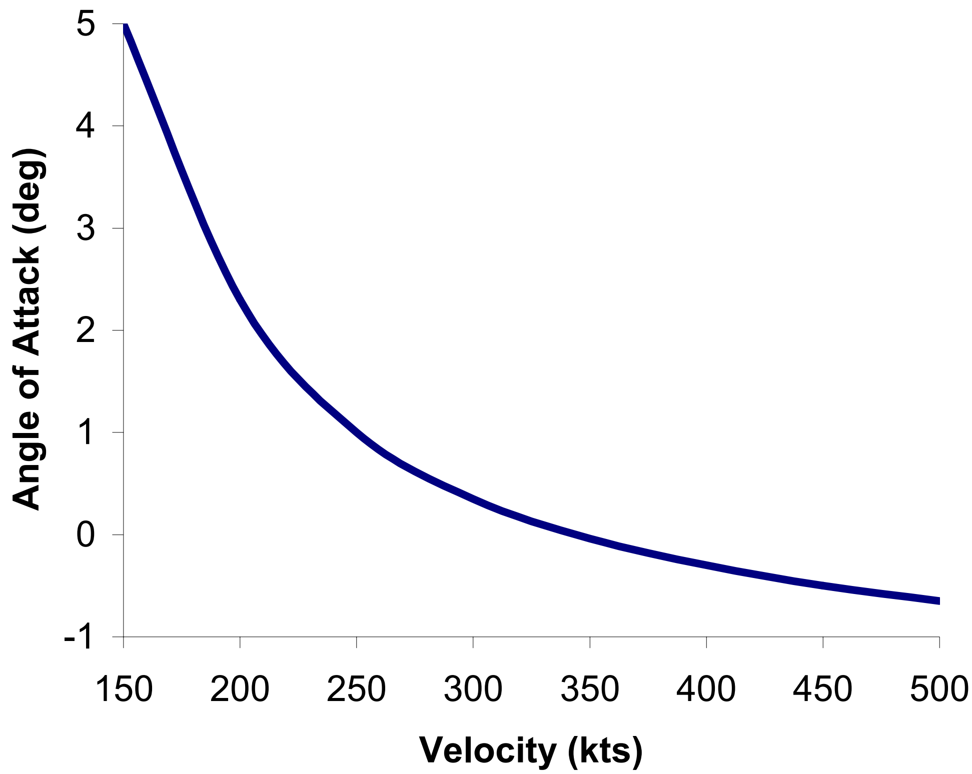



**Figure 17 Centerbody Required Angle of Attack**

As the body is launched into undisturbed air, angle of attack is defined as the angle between the launch angle and the body's mean chord line. Below 150 kts the body is not able to generate enough lift to support its own weight. This will result in a reduction in the apogee height predicted by the trajectory analysis program.

The centerbody is naturally unstable in the climb. As a result control inputs must be made to keep the body heading in the required direction. There was a concern that control inputs at high velocity would result in an excessively large drag. Analysis showed (Figure 18) that deflections below around $4^o$ result in a negligible drag increase. However, this small drag will still result in a small reduction in the apogee height.

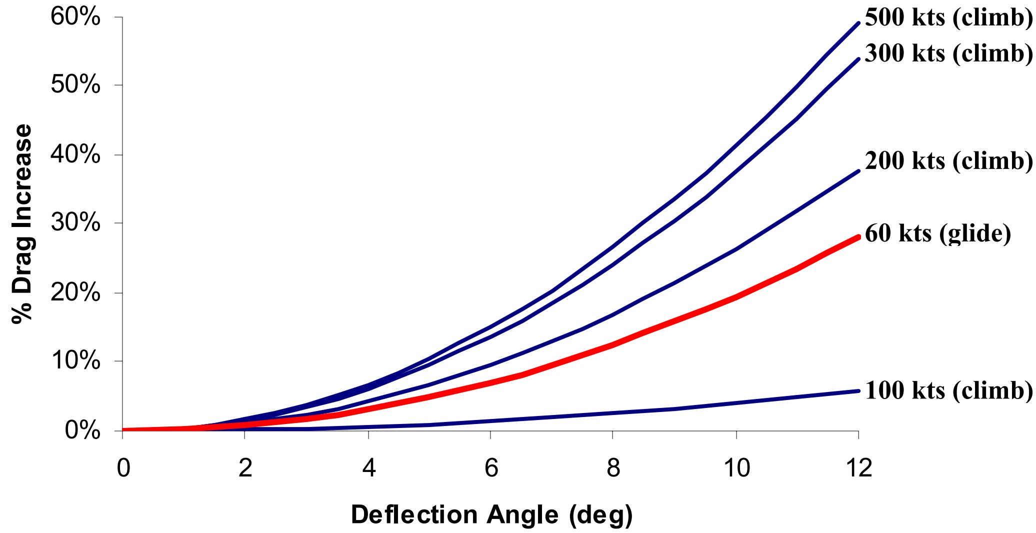



**Figure 18 Percentage Drag Increase due to Control Deflection**

Additional factors affecting glider performance are the atmospheric conditions encountered and the control surface deflections necessary to counteract them.

## 2.6 Weight Analysis

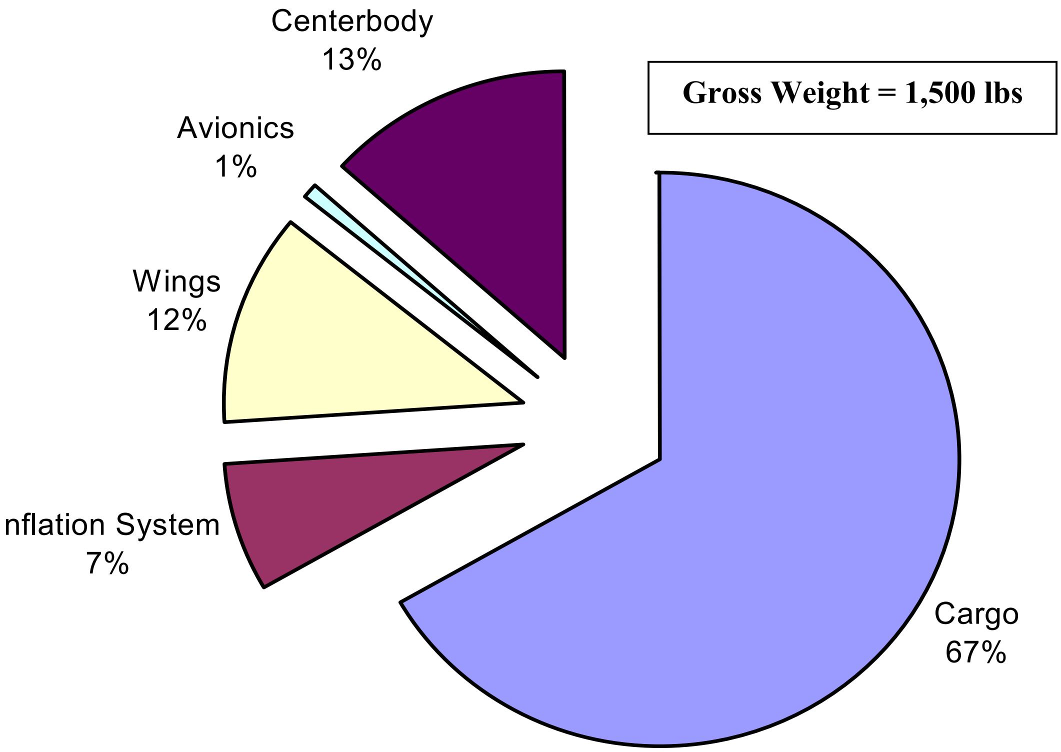



**Figure 19 ALDS Weight Breakdown**

| Component | Weight (lbs) |
|---|---|
| Cargo | 1,000 |
| Inflation System | 110 |
| Wings | 180 |
| Avionics (inc Batteries) | 10 |
| Centerbody | 200 |

**Table 2 ALDS Weight Breakdown**

ALDS is designed to carry a payload of 1,000 lbs. An initial estimate of the empty vehicle weight was 500 lbs, resulting in a total weight of 1,500 lbs (Figure 19, Table 2). The 'Wing' and 'Inflation System' weight were scaled up from the ERADS 1,000 lbs prototype[7]. The centerbody weight was calculated from CAD analysis.

## 2.7 Centerbody Configuration

The cargo, gas bottles, wing pods, avionics and batteries have to be placed within the centerbody for launch. Several configurations were analyzed and the optimum for space and center of gravity considerations was chosen (Figure 20). Space required for batteries and avionics packages is relatively small compared to that for the cargo and gas bottles. These systems were located in a large compartment aft of the cargo to control center of gravity.

The cargo needs to be packed tightly upon launch. One option is to suspend the cargo in foam and build the centerbody around it. An alternate option is to use a bag, which inflates prior to launch securing the cargo.

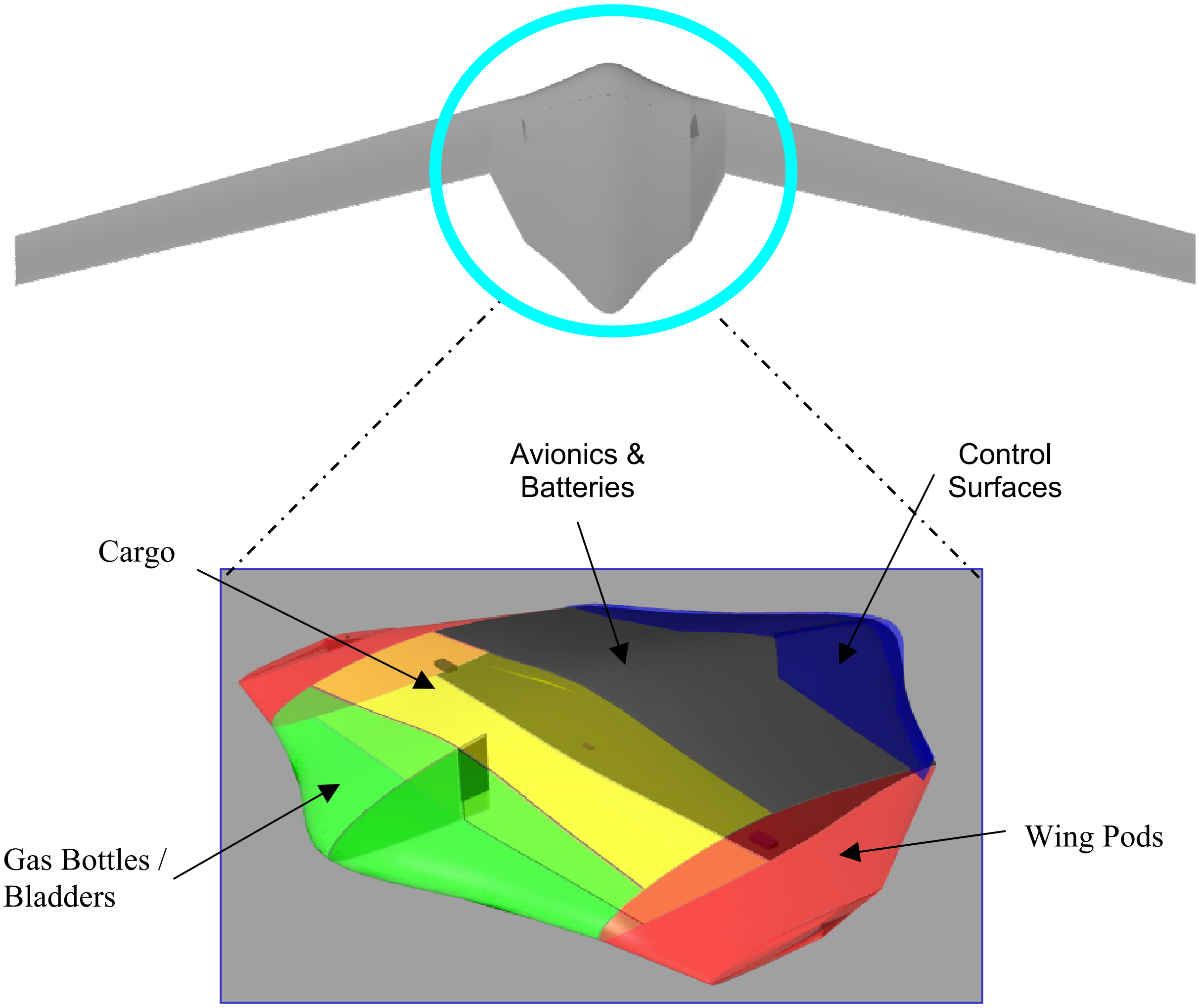



**Figure 20 Centerbody Configuration**

Cross sectional areas were confirmed by CAD (Figure 21).

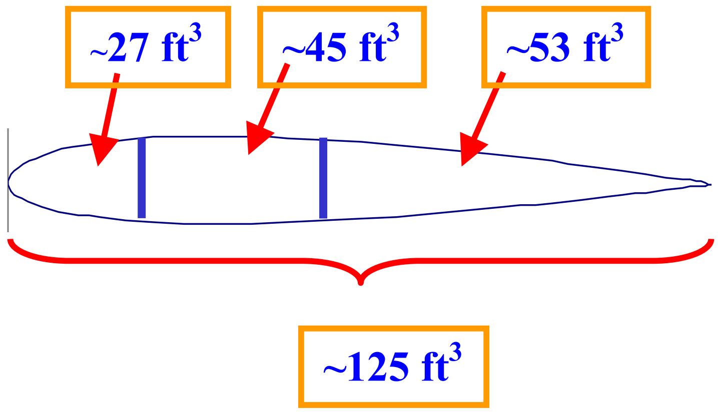



**Figure 21 Cross Sectional Area**

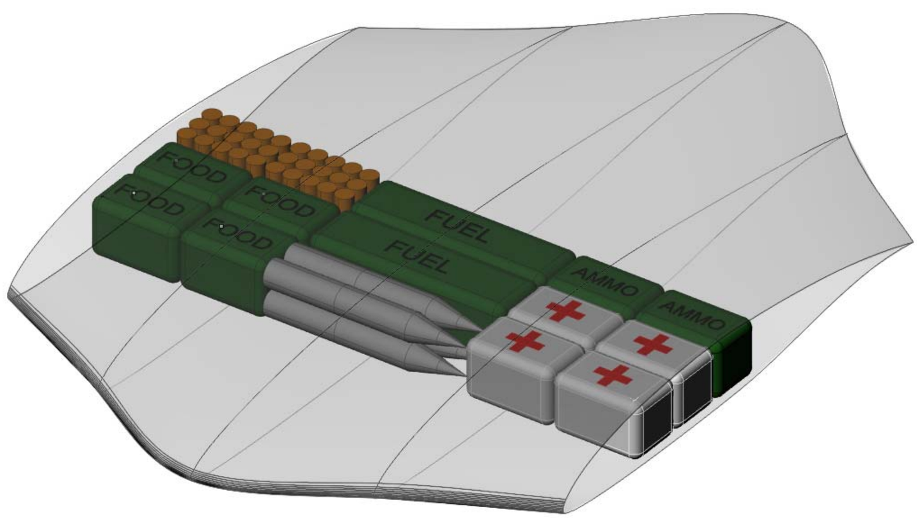



**Figure 22 Cargo Bay Location**

### *2.7.1 Gas Bottles and Bladders*

In order to supply sufficient pressure to inflate the wings, the ALDS glider requires a way to store gas under pressure. The standard way to do this is using gas bottles. However, the volume of rigid bottles severely impacts the ship space requirements. The ship is designed for a four day mission launching around 200 gliders per day. This means up to eight hundred bottles would have to be stored. To reduce the volume required, gas bladders would be a reasonable option to pursue for this application. Currently there are no collapsible gas bladders available that would hold the pressure needed to inflate the wings at apogee, however there are high strength materials available, such as Ultra-High Molecular Weight – Polyethylene (UHMW-PE) that could theoretically be manufactured into sufficient bladders for such a use.

### 2.7.2 *Avionics*

Avionics needed to control and navigate the ALDS glider throughout its flight are well within the capabilities of current technology. Development would focus on production to minimize cost.

Vertigo have demonstrated an ability to land their parafoil air drop packages within 20 m of the intended point. Accuracies within 10 m are expected to be possible within the next 10-15 years. Sophisticated systems such as guided missiles can achieve greater accuracy because they maintain control to the point of impact. Simple GPS combined with a fly-by-wire system will allow ALDS to be fully controllable vehicle and a high accuracy is believed to be feasible.

High accuracy is required because ALDS may be deployed to a zone with high foliage coverage. This means only a limited clear area may be available to land ALDS. There may also be large deviations in the local terrain and ALDS needs a relatively smooth area to land. Simple forms of terminal guidance that allow for more rapid descent may alleviate these problems.

## 2.8 Structural Design

A structural analysis was performed for the ALDS centerbody using traditional stiffened plate aircraft construction. The stringers, struts and ribs form the structural skeleton of the centerbody. This structure is then covered with an aluminum skin.

A basic structure was designed to withstand the loads experienced in launch, cruise and landing. Landing analysis showed that additional material is required to protect the cargo from forcible disbursement.

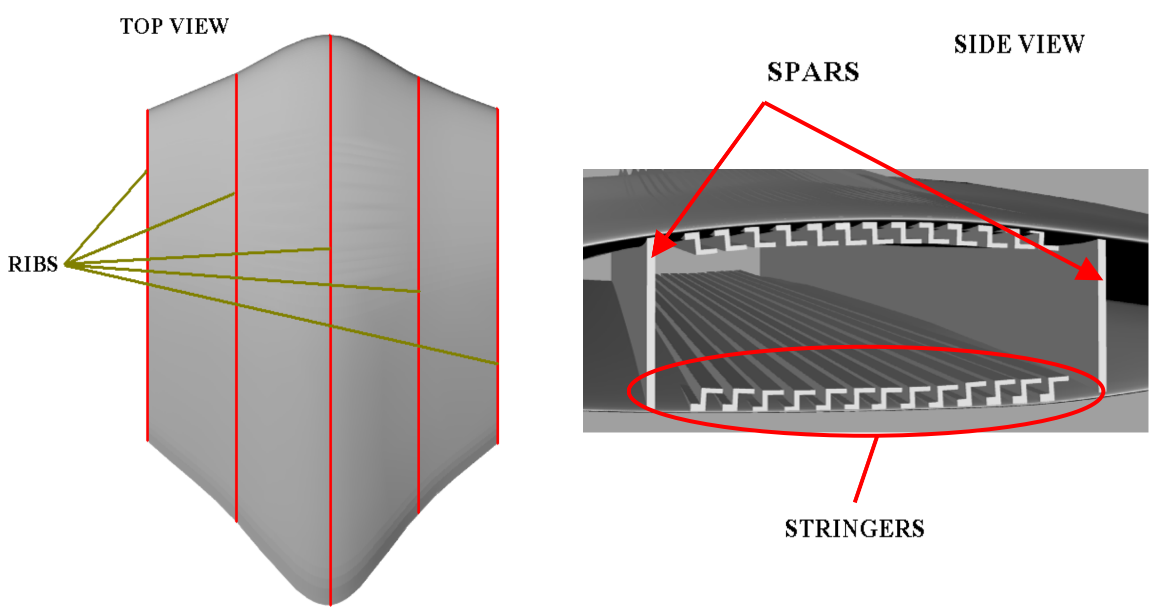



**Figure 23 Centerbody Structural Design**

A wing box analysis was performed and several geometric simplifications were made to the centerbody prior to calculations. Initially, the chord length of the glider varied from a central chord of 14.8 ft to a chord of 8.7 ft at the outer tips. Additionally, the front profile was a near ovular shape having maximum and minimum thicknesses of 1.6 ft and 1.3 ft respectively. For calculation purposes, the glider was assumed to be a rectangular shape (Figure 24).

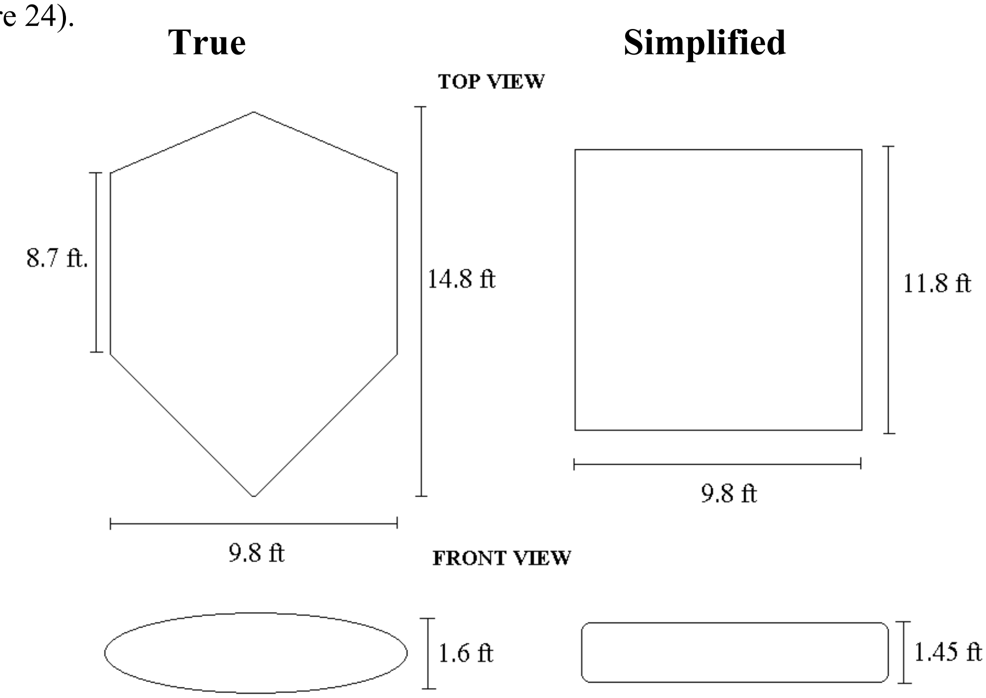



**Figure 24 Structural Simplications**

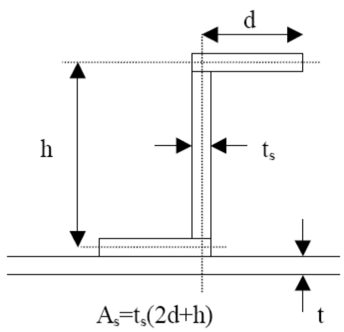
A spreadsheet was set up to calculate the weight of the centerbody structure of the glider (Table 3).

| Component | Weight (lbs) |
|---|---|
| Upper Skin | 50.2 |
| Lower Skin | 50.2 |
| Stringer (1x) | 0.16 |
| Leading Edge Spar | 19.4 |
| Trailing Edge Spar | 19.4 |
| Spar Cap (1x) | 1.1 |
| Rib (1x) | 21.8 |
| Total Structural Weight (lb) | 223.8 |

**Table 3 Centerbody Weight Breakdown**

The structural members of the centerbody were sized using basic wing box theory (boom-panel analysis). In this method, the wing box was assumed to carry all of the loading.

Several loading cases were analyzed in the design to ensure the glider survived the entire mission. The anticipated loads on the glider were due to acceleration, steady-level flight and impact upon landing. The stresses acting on the wing box were calculated for each load case. These values were then compared to the allowable figures dictated by the material properties. An iterative process was used to size the members, ensuring all stresses were below the critical values. The final design included 2 spars, 5 ribs and 15 stringers, per upper and lower surface (Table 4).




| | |
|---|---|
| **Leading & Trailing Edge Spar** | |
| **Thickness (inches)** | 0.059 |
| **Height (inches)** | 22.92 |
| **Stringers (identical members)** | |
| **Thickness, $t_s$ (inches)** | 0.04 |
| **Height, h (inches)** | 0.2 |
| **Flange, d (inches)** | 0.11 |
| **Quantity per surface** | 16 |
| **Distance between stringers (inches)** | 2.12 |
| **Skin Thickness (inches)** | 0.08 |

**Table 4 Structural Member Sizing**

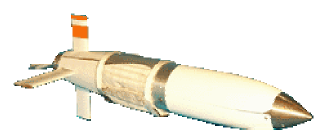
## 2.9 Detectability

One of the advantages of the ALDS glider over other logistics delivery systems is its low detectability. Having no engine, it has no infra-red or acoustic signatures. It has a small radar-cross section due to the small body and long, slender wings. Additionally, the absence of junctions between surfaces (due to the flying wing design) makes the ALDS glider a poor radar reflector.

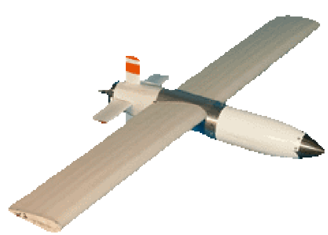
# 3 Inflatable Wing Technology

Fundamental to the flying wing ALDS concept are inflatable wings that deploy at apogee. The structural integrity of these wings is provided by a series of hollow spars filled with high-pressure gas. The skin of the wing is formed by foam and cloth stretched over these spars. Wing spars on currently available inflatable wings are inflated using compressed gas. ALDS also has a very low wing loading (6.1 lb/$ft^2$), which allows the wings to withstand the aerodynamic loads.

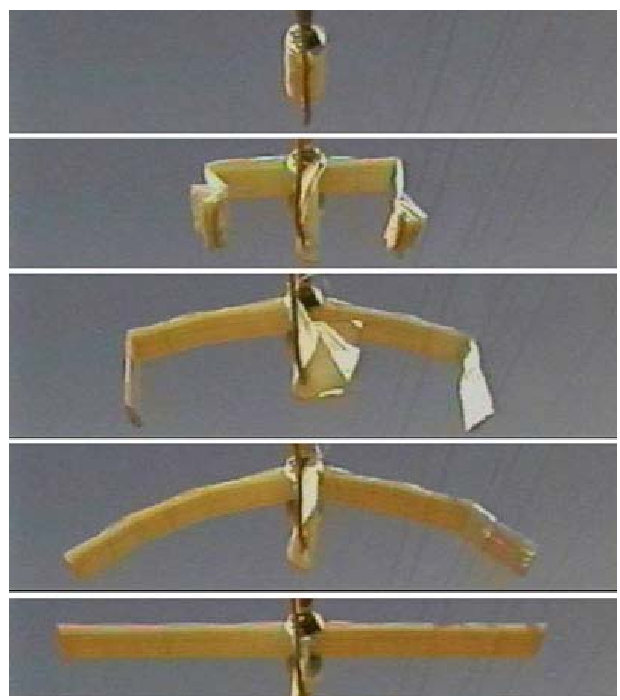
Inflatable wings have been demonstrated in several applications. Vertigo, one of the manufacturers of these wings, designed and developed a Gun Launched Observation Vehicle (GLOV)[7] (Figure 25). The vehicle, with wings deflated, is launched as a projectile from a 5” gun. Compressed gas stored onboard at 300 psi is used to inflate the wing spars in-flight to a pressure of 145 psi. Inflation of the GLOV wings occurs in less than a second with the vehicle traveling at 67 kts. Inflated wingspan is 67 inches. With the inflatable wings deployed, flight is sustained using a small propulsion engine. The autonomous vehicle is designed to carry sensors and communications gear to provide fire control and damage assessment.



GLOV with wings packed



GLOV with wings inflated



Wing deployment sequence

**Figure 25 Vertigo GLOV**

Vertigo has also designed the Extended Range Aerial Delivery System (ERADS). This aircraft will be parachute-dropped from a cargo aircraft such as the C-17. The wings will be inflated while suspended under parachute. The final design will carry 12,000 lbs of payload up to 40 miles. A sub-scale science and technology demonstrator (sponsored by the US Army) carrying 1,000 lbs of cargo has been built and flown (Figure 26).

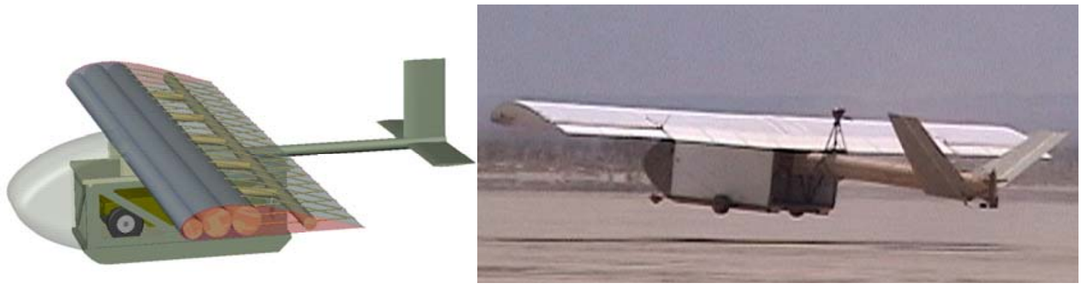


**Figure 26 Extended Range Aerial Delivery System**

NASA also fitted inflatable wings to an unmanned vehicle that was air dropped to demonstrate inflatable wing technology (Figure 27). The technology is also being applied to a prototype Mars probe.

**Figure 27 NASA Inflatable Wing Technology Demonstrator**

## 3.1 Internal Wing Structure

There are two configurations of internal wing structure. Tubular spars use braids or weaves to help resist the wrinkling moment. These tubes are then surrounded by multi cell foam and covered by a skin to give the airfoil shape (Figure 28). This approach allows for a better adaptation to moving control surface technology.

**Figure 28 Tubular Spar Inflatable Wing Structure**

The multi spar approach uses several inflated spars that intersect with each other. The internal pressure and the material modulus of elasticity determine wing stiffness. This

allows for flexibility in the design and offers the ability to change certain characteristics to create a stiffer wing. This approach allows for a better adaptation to morphing technology. However, a greater volume of gas is required and only simple airfoil shapes can be used.

**Figure 29 Multi Spar Inflatable Wing Structure**

## 3.2 Control Options

Morphing allows the inflatable wing to act as a control surface by creating deflections. Two types of morphing techniques were examined.

*Bump Flattening*

Morphing of an inflatable wing can be achieved using a technique called “bump flattening” where actuators are applied directly to the wing restraint. A piezoelectric actuator is bonded first to a rigid substrate and then to the wing restraint fabric. When energized, a force is generated perpendicular to the plane of the actuator, resulting in a flattening of the individual bumps caused by the wing spar spacing (Figure 30). By flattening individual bumps in series, a net increase in run length is generated, resulting in deflection of the wing’s trailing edge. The actuator is required to overcome the internal inflation pressure.

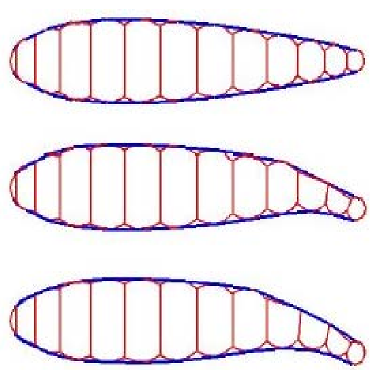


**Figure 30 Control Using Bump Flattening**

*Trailing Edge Deflections*

The actuators reside under the wing skin, providing an uninterrupted surface to the air stream. The actuators expand or contract in response to the application of a positive or negative voltage (Figure 31). By applying opposite polarity voltages to the upper and lower actuator, the substrate is caused to flex. This design does not need to overcome the internal pressure of the wing in order to achieve the deflection, as the deflection occurs in the skin.

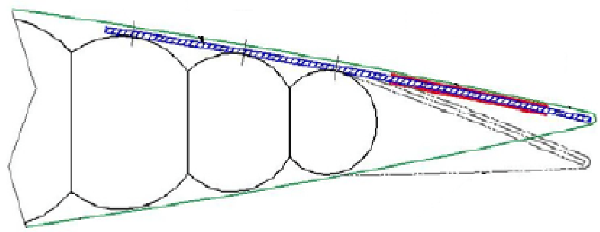


**Figure 31 Trailing Edge Deflection**

*Moving Control Surfaces*

After discussion with Vertigo, it was discovered that moving control surfaces on an inflatable wing presented no major problem (Figure 28). Due to the ease of design and construction, this would be the preferred near term method for application on the ALDS vehicle. Moving surfaces are also easy to integrate on a flying model.

## 3.3 Braided Spars

The current focus of Vertigo is on the development of braided spars. Braiding produces a tubular structure reinforced by fibers orientated at an oblique angle, the "Bias" angle, as measured from the tube axis[7] (Figure 32).

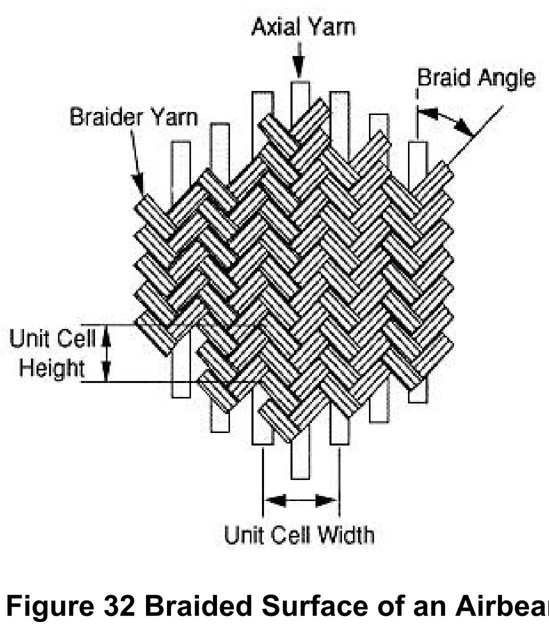



**Figure 32 Braided Surface of an Airbeam**

An airbeam is composed of a braided spar to withstand hoop stress and an internal gas barrier to contain the inflation gas. Finally, spar caps are used for axial reinforcements (Figure 33).

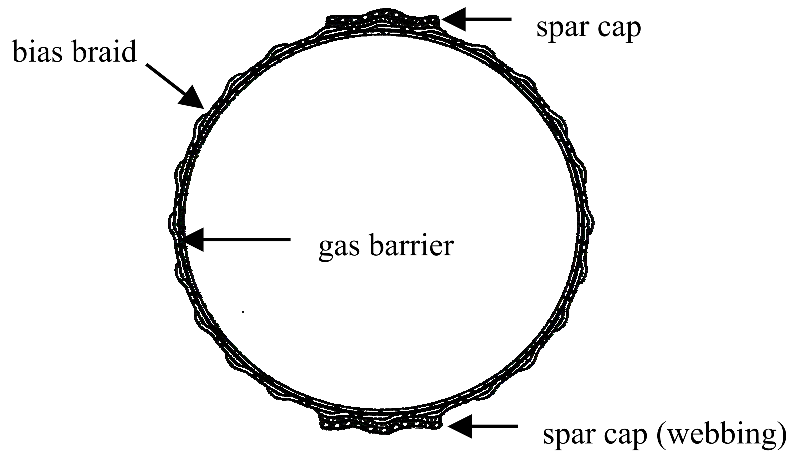



**Figure 33 Section of Braided Spar**

## 3.4 Bending Strength and Inflation Requirements

The inflatable wing must be able to support the entire bending moment without "wrinkling." Wrinkling occurs when a fiber within a beam reaches zero tension. This condition is known as the onset of wrinkle and causes large deflections of the wing.

The wrinkle onset moment is a function of diameter, bias angle and internal pressure, Equation (0.8).

$$M_{wrinkle} = \frac{\pi}{8} P d^3 \left(1 - \frac{2}{\tan^2 \beta}\right) \tag{0.8}$$

Bias braiding is used to restrict pressures in the circumferential direction of the tube caused by inflation. Increasing the bias angle increases the "strength" of the spar as there is a larger contribution to resistance of axial stress. However, increasing bias angle decreases the allowable hoop stress, hence pressure (Figure 34).

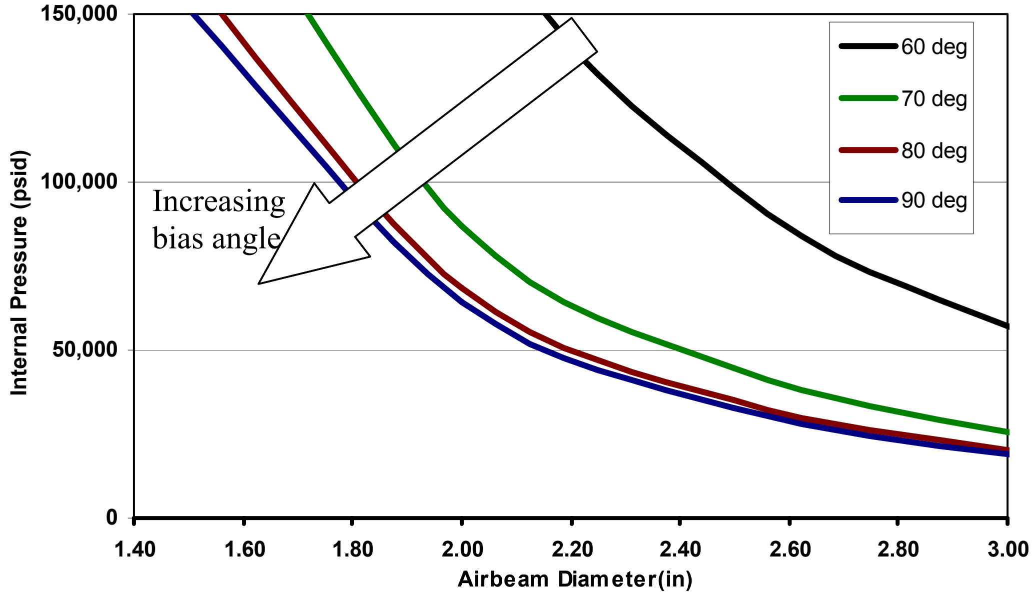



**Figure 34 Required Inflation Pressure of Airbeam**

## 3.5 Application of Inflatable Wing Technology to ALDS

Previous applications of inflatable wing technology have used relatively simple wing shapes on small vehicles. By comparison, the ALDS wing is larger and more sophisticated. Inflatable wings of this size and sophistication have not been demonstrated. A suitable investment in technology development is required to bridge the capability gap between existing inflatable wings and the ALDS concept.

Vertigo were presented with the ALDS design and given an opportunity to offer their expertise. They believe their technology to be a concept enabler for the ALDS design and envisage no major problems. It was commented that a 70 ft wingspan is at the upper limit of current technology, but still feasible. A previous design shows a swept wing application (Figure 35).

**Figure 35 Swept Wing UAV**

The inflation of 30 ft wings is expected to take approximately 10 s. Hot gas would aid in rapid inflation and also deal with the altitude effects, i.e. no topping up would be required.

The size of the gas bottle would be acceptable. In the ERADS demonstrator (an aircraft roughly half the size of the ALDS glider), a scuba-sized filament wound tank was used. It is desired to use air for ALDS due to the space requirement of onboard assembly. Use of air means the launch ship needs only a compressor on board to inflate the gas bladders. However, roughly twice the weight of air is required over that of helium.

It was expected that a prototype set of wings could be developed for around $25,000, yet a production line could reduce the cost to below $10,000. Although expendability was the initial assumption for ALDS, the wings could be recovered and packed to a small size. The wings tend to be quite tough and could withstand the landing undamaged.

Reflex camber airfoils present a new challenge, as there is the tendency for the reflex section to straighten out due to the large pressure. Standard NACA airfoils are easier to develop. This is a possibility for ALDS but the stability and trim analysis would need to be revisited to calculate the new wing parameters. Using standard airfoils means that negative lift would be required at the tips, as the original ALDS paper described[3]. The off-design performance of wings with negatively loaded tips is quite poor. Reflex airfoils are better from a performance point of view and efforts should be made to use these.

# 4 Trimaran Ship Design

## 4.1 Mission Profile

In determining the type of ship required for ALDS, the overall mission profile for the ship was determined (Figure 36). It is assumed that the ship carries enough fuel to travel from CONUS to the Sea Base where it will be refueled and supplied. The Sea Base could potentially be located anywhere; however, for this study it was assumed to be 250 nm from shore. This distance allows the sea base to be outside of small missile range, while still being close enough for the V-22 Osprey to make trips to shore, refuel on the ALDS launch ship, and return to the Sea Base. The ALDS ship will support the V-22 Osprey mission by providing at least one helicopter pad and refueling capabilities. After being fueled and supplied at the Sea Base, the ALDS launch ship begins traveling towards the shore. A high-speed ship (approximately 40 kts) is required to efficiently deliver the supplies to the troops ashore. At approximately 20 nm from the coast the ship begins traveling parallel to the coastline. This distance allows for the ship to be out of gunfire range, and the ship will either be in an assumed safe area, or escorted for protection.

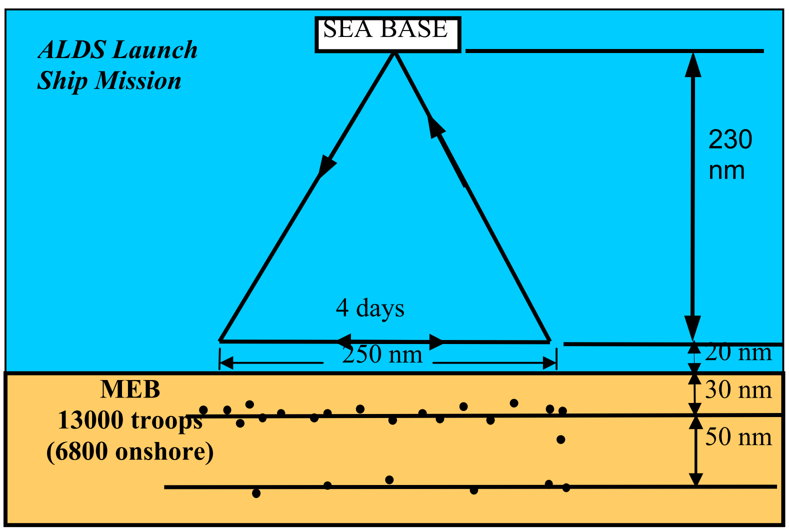



**Figure 36 ALDS Launch Ship Mission**

The primary requirement of the ALDS mission is to provide 100 % of the dry cargo needs of one Marine Expeditionary Brigade (MEB), approximately 6,800 troops ashore. Studies show that these forces require approximately 75 short tons of dry cargo each day[8]. A secondary mission of ALDS is to provide 10 % of the wet cargo needs, water and fuel, for the troops that are further inland and in hazardous areas where manned V-22 Ospreys are not a safe option. To increase the range of the ALDS glider, disposable rockets are included for 15 % of the vehicles. For ALDS to deliver all of the dry cargo and 10 % of the wet cargo, 233 gliders will be launched each day.

The main geometrical requirement of the ALDS launch ship is for the length to be at least

600 ft long. This estimate was concluded for two reasons. First, the linear induction motor requires a length of approximately 365 ft to achieve the desired velocity. Also, the machinery rooms were estimated to be 200 ft long based on X-Craft data, which is a ship with similar power requirements. Based on this length and approximate displacement calculations, the overall mission was determined to be four days for this study. Using typical length to depth ratios, this length yields a depth of about 40 ft.

## 4.2 Ship Selection

When considering the type of ship needed, three main requirements were identified:

1) A high-speed ship was needed to make the mission efficient,
2) A long hull was needed for the launcher,
3) A relatively large amount of deck space was required for stowage of material and the onboard assembly process.

One option considered was a monohull due to its conventionality and the low risk associated with such a hull. Some of the disadvantages of monohulls are that they are typically short for stability purposes, they do not have a large amount of upper deck space and they would need considerable power to reach the required speeds. For these reasons a monohull was not chosen. Secondly, a catamaran was considered due to its large deck space. However, it has more deck space than required and is also typically a short ship. Finally, a trimaran was considered and the conclusion was drawn that this would be the best option to pursue. A trimaran typically has a long slender hull that allows for high speeds and easily lends itself to the launch tube. Another advantage of a trimaran is that the side hulls allow for extra deck space, which is efficient for the assembly process.

## 4.3 Typical Day Breakdown

A typical 24 hour day breakdown would include time to launch the gliders, travel time along the coast, and general maintenance time. Since ALDS will deliver 100 % of the dry cargo and 10 % of the wet cargo needs for one MEB, 233 glider launches per day are required. Launches will occur every two minutes resulting in 7.75 hours of launch time. The ship is assumed to travel 250 nm along the coast at 40 kts for 6.25 hours. The remaining 10 hours of the day will be used for maneuvering time, emergency launches, trips to and from the sea base, ALDS glider assembly and general maintenance.

## 4.4 Payload

The payload was calculated (Table 5) using data from reference 8 and by making appropriate assumptions.

| Type of Cargo | Amount of Cargo (short ton) | Total Percentage of Cargo |
|---|---|---|
| Dry Cargo | 75.0 | 24% |
| Wet Cargo | 41.5 | 13% |
| Rocket Weight | 3.5 | 1% |
| Glider Weight | 58.0 | 19% |
| V-22 Fuel | 136.0 | 43% |
| **Total** | **314.0** | **100%** |

**Table 5 Daily Cargo Requirements**

The dry cargo includes food, ammunition, medical equipment and other supplies that a MEB requires. The wet cargo includes 10 % of the fuel and water requirements for the MEB. The glider weight accounts for all of the components of the glider except for the rockets which analysis showed to be negligible. The most significant component of the payload is fuel to assist the V-22 Osprey mission.

## 4.5 Cargo Handling

Sea based logistics presents the challenge of stowing and retrieving cargo onboard ships. The trimaran launch ship functions as a distribution center providing for all of the dry cargo needs and some of the wet cargo needs of troops ashore. Many onboard material handling difficulties arise as a result of the high level of automation required to efficiently organize and distribute large quantities of cargo to troops ashore. One initial problem is the transfer of standard 20 ft tonnage equivalent unit (TEU) containers and other cargo from a Sea Base platform to the trimaran launch ship in high sea states. Feasible, near term solutions to some of the cargo transfer issues include stabilized cranes equipped with anti-sway systems (currently in development) and retractable ramps (currently in use). The handling of cargo in containers or pallets onboard the ship is another problem during travel. Industry has developed automated cargo handling technology and successfully implemented many automated processes that can be applied to the ALDS launch trimaran. Some of these automated processes include conveyor belts, elevators, robotic pickers, and radio frequency identification (RFID). Even though such cargo handling techniques exist, the application of this technology onboard a ship is a new challenge. Trends indicate that cargo will arrive to the sea base in TEUs and be broken down into smaller cargo units such as pallets. However, whether the containers will be broken down into pallets at the sea base or onboard the ALDS ship is undetermined. Three cargo handling options for maneuvering the dry cargo onboard the ship and into an ALDS centerbody were identified.

#### 4.5.1 "Container Depot" Option

The "Container Depot" concept for maneuvering cargo involves loading TEUs onto the ALDS launch ship. The trimaran connects to the sea base platform with a retractable ramp, located on the second deck at the stern, over which a container handler transports the containers from the sea base to the ship. These containers are placed onto a roller conveyer that leads into the container stowage room. This container stowage room occupies the entire cross-deck at this level. The roller conveyors within the container stowage room are able to move two dimensionally in the fore/aft and port/starboard directions so that containers can be docked and removed as required. The containers are docked in the cargo handling room along the ship's sides until all of the cargo within the container is removed. To enable an automated picker to select specific cargo directly from the container and place it into the ALDS centerbody, the containers will need to be configured to open on the sides, as well as internally configured as accessible storage.

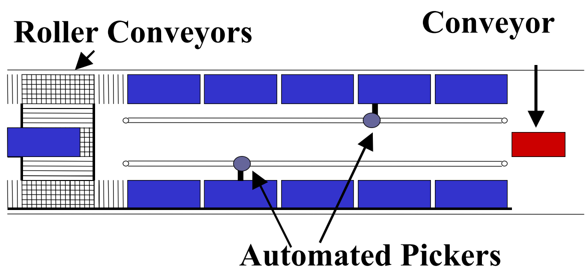



**Figure 37 "Container Depot" Option**

Unloading cargo from containers and reorganizing it for selection is a time intensive task. The main advantage of the "Container Depot" cargo handling option is that cargo arrives pre-configured for selection within each TEU. These containers arrive on the ship, recognized by RFID, and are then transported within the ship after a computer database identifies the correct location for each container. This type of arrangement allows for the efficient transfer of cargo and eliminates the need to unpack and reorganize cargo on the ship.

Disadvantages of the "Container Depot" option include the additional weight of the system, increased powering requirements and the need for specialized containers. The amount of added structure to support TEUs and the necessary conveyors increase the weight of the ship and ultimately change the resistance and propulsion characteristics. It is also unlikely that current TEU containers will be reconfigured to open on the sides. Additionally, an internal accessible storage configuration does not maximize the use of a container's potential volume. A final disadvantage is that maneuvering containers while the ship is underway is highly complex and undesirable.

#### 4.5.2 "Vending Machine" Option

The "Vending Machine" option involves a container stowage concept similar to that of the "Container Depot" option. However, in the "Vending Machine" option, containers

are opened at the end and smaller cargo units are distributed to several rooms. These smaller units are packaged in such a manner that automated selection is possible. Amongst the vending machine rooms are several carousel rooms used for standardized cargo items, such as food in the form of MREs and medical supplies. These cargo units rotate after all of the standardized cargo items have been removed. There is also a room with an automated picker for less standard cargo items such as spare machinery parts and tools. Each of these rooms contains a conveyor belt leading to a centralized location where the selected cargo is arranged and placed into an ALDS centerbody. This concept gets its name from its similarities to a common vending machine, where all requests arrive at a common location. One difference is that this cargo handling technology allows multiple items to move simultaneously.

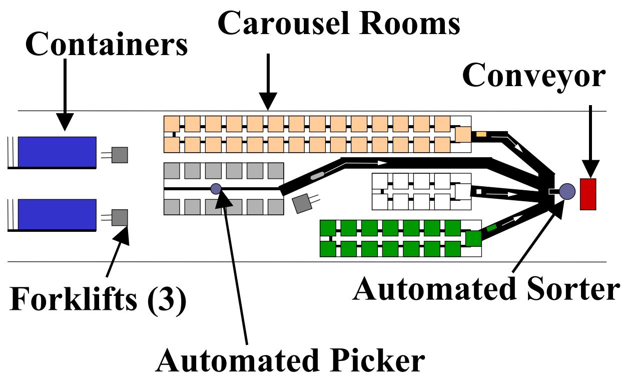



**Figure 38 "Vending Machine" Option**

One advantage of this cargo handling option is the time saved due to the simultaneous movement of cargo items towards the ALDS centerbody. This option allows ALDS to be flexible enough to function as an on demand delivery system. Another advantage of this option is that it uses standard TEUs instead of specialized containers. This option also promotes a high level of automation for the cargo handling process onboard the ship.

The major disadvantage of the "Vending Machine" option is its complexity. While a high level of automation onboard the ship is desirable, it is necessary to take into account system feasibility.

### *4.5.3 "Hallway" Option*

The "Hallway" cargo handling option is unlike the previous two options in that it does not involve bringing containers onboard the ship. Containers are opened and broken up into pallets at the sea base. Forklifts transport the pallets over the trimaran's retractable ramp directly into the ship's cargo handling room. The pallets are placed in specified locations in aisles running longitudinally in the ship. Once all of the pallets are loaded from the sea base platform and the ship is underway, an automated picker selects the requested cargo and places it into the ALDS centerbodies.

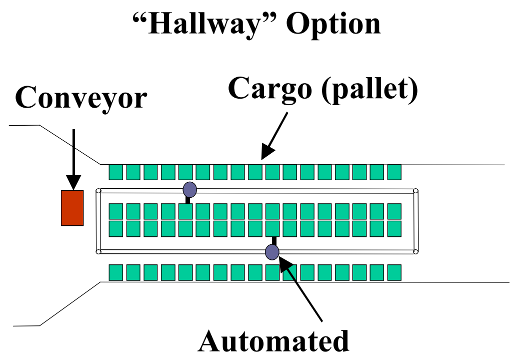



**Figure 39 "Hallway" Option for Cargo Handling**

Out of the three cargo handling options, the "Hallway" concept was chosen in the study for a variety of reasons. Primarily, this option does not involve the handling of containers onboard the ship. Leaving the containers at the sea base results in less required deck space due to the elimination of the container stowage room. This deck space reduction along with the elimination of containers results in significant structural weight savings.

There are still disadvantages of the "Hallway" cargo handing option. The first is the manpower required to drive pallets onto the ship via forklifts. Another disadvantage is that this arrangement does not maximize the potential space per pallet. Also, while this system is the least complex of the three options, it still requires levels of automation that have not yet been achieved onboard of a ship.

## 4.6 Glider Manufacturing/Assembly Process

The centerbody of the ALDS glider is a large and hollow structure and the ALDS mission requires the launch of 233 of these gliders each day for four days. The large volume requirement resulting from storing 932 assembled ALDS gliders onboard the ship makes the off board fabrication unattractive. To address this problem, methods of manufacturing and assembling the ALDS glider onboard the ship were investigated.

The two main manufacturing options considered in this study were Plastic Injection Molding (PIM) and Stamping. PIM involves heating thermoplastics in a heat chamber and then forcing that material into a mold through the use of a pressure gradient[9] (Figure 40). Advantages of this technology include its high production rates, repeatable high tolerances, minimal labor costs and minimal scrap losses. However, this technology has the disadvantage of its limitation to plastic materials, hindering the structural optimization of the ALDS glider. This technology also has not been developed for something as large as an ALDS centerbody.

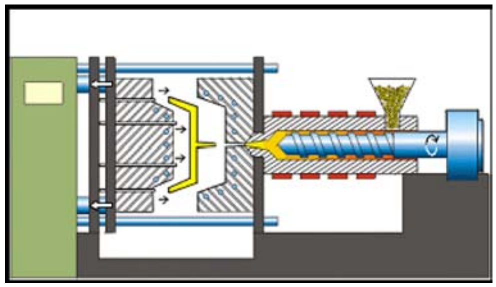


**Figure 40 Plastic Injection Molding Schematic[10]**

The other manufacturing option considered in this study was stamping (Figure 41). Conventional stamping machines exist, but are limited in molding capabilities because aluminum wrinkles and tears once stretched past a certain strain level. However, science has shown that aluminum stamping can be achieved at higher velocities. This new technology is termed High Velocity Electro-Magnetic Stamping (HVEMS) and allows aluminum to be stretched to higher strain levels[10]. One major advantage of this new technology is that it allows the stamping of aluminum sheet metal, which is a preferred material for aerospace applications. This stamping technique is very repeatable and efficient. However, the integration and operation of a manufacturing process into a ship design is complex. Also, HVEMS does not allow the generation complex shapes and this technology has not yet been developed for something as large as an ALDS centerbody.

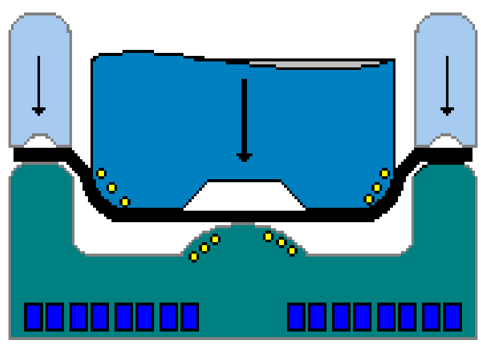


**Figure 41 HVEMS Schematic[10]**

Since the technology has not been developed for a complete manufacturing and assembly process, a near term assembly-only process was identified. This involves separating each ALDS centerbody into a top and bottom half and then stacking these separate halves within each other in a manner similar to packaged plastic cups. A volume analysis was then conducted comparing the volume of these stacks to the volume of pre-assembled ALDS centerbodies for a period of four mission days (Figure 42). Also included in the

volume analysis were theoretical estimates for PIM and HVEMS based on the volume of the raw materials and the size of the machinery required.

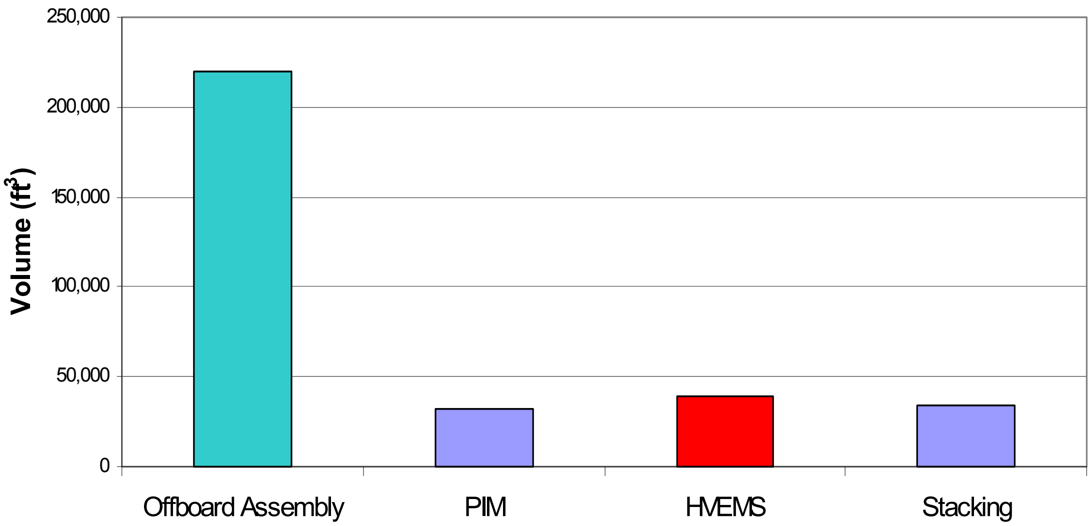



**Figure 42 Centerbody Assembly Volume Comparison**

Assembling centerbodies off-board and storing them on the ship requires a much larger volume than assembling centerbodies onboard the ship. The volume requirements of the onboard options are similar, making Stacking a near term solution due to its current availability and simplicity. However, this concept still presents problems. The ALDS sections are too large to fit into pallets or containers. This makes maneuvering large stacks of these bodies onto the ship very difficult. Stacking also requires ribs, spars, and other components of the centerbody design to be snapped into place that could be directly incorporated into a plastic mold. This complexity leads to an increase in required manpower and a larger industrial crew onboard the ship. Due to its complex molding capabilities, PIM would eliminate some of the assembly steps and increase the level of automation on the ship. With research and development, PIM is considered a far term solution.

Assuming a near term solution, a conceptual assembly room onboard the ship was developed. This assembly room makes use of the extra deck space created by the trimaran hull cross-deck (Figure 43).

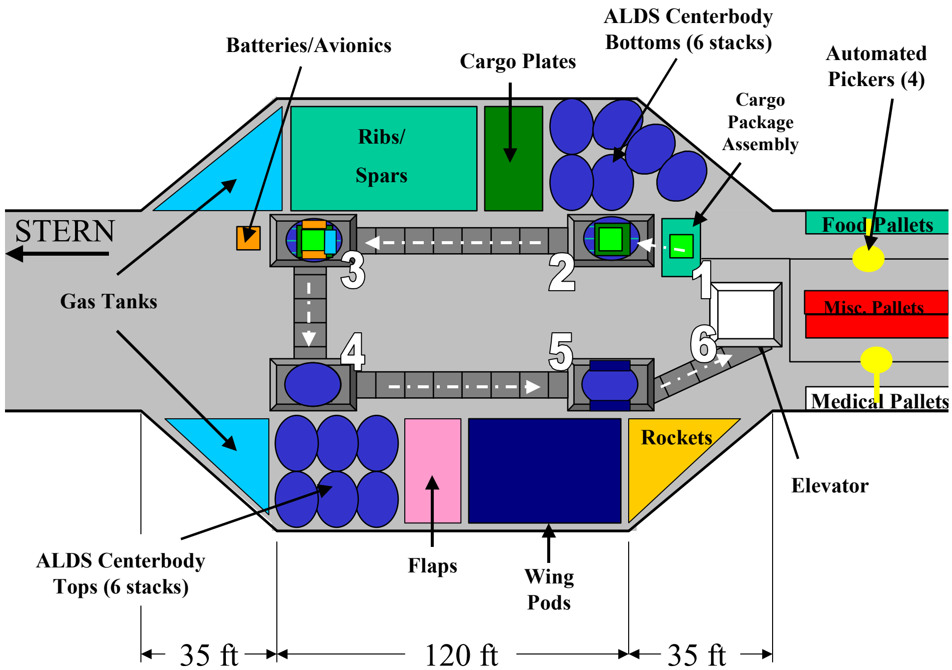



**Figure 43 ALDS Onboard Assembly Process (Overhead View)**

The ALDS glider assembly and delivery process is broken down into six distinct steps. The first step involves the aforementioned cargo handling room. The schematic depicted here shows a portion of this 250 ft long cargo handling room based on the "Hallway" option discussed earlier. In this first step, four automated pickers select the desired cargo from the food, medical and miscellaneous pallets and drop it off at a common location where the required 30 $ft^3$ cargo package is assembled. This cargo package is then placed in the ALDS glider during its construction, comprised of the next four steps that occur in a counterclockwise assembly line fashion. The first of these steps involves the attachment of the ribs and spars within the ALDS centerbody bottom, as well as the placement of the cargo plate. The cargo package is then loaded onto this cargo plate, and the partially assembled ALDS glider is placed on a conveyer belt and transported to the next assembly step. During this third step, batteries, avionics, and gas tanks are placed into the centerbody. Note that the batteries and avionics are very small in size and can be transported and stored as a single pallet. The fourth step of the ALDS glider assembly and delivery process involves the attachment of the centerbody top and the installation of flaps. The glider is then moved to the fifth step where the inflatable wing pods are attached. A rocket can also be attached to the glider at this point to augment its range. The glider is then delivered to the linear induction motor located at the bottom of the ship using an elevator. In order to clear the deck for cargo transfer at the sea base, all conveyer belts will be on rollers. An alternative to conveyer belts is bins attached to tracks or an overhead rail.

## 4.7 Linear Induction Motor Integration

Another major feature included in the ALDS launch trimaran design is the linear induction motor. A linear induction motor (LIM) is simply a rotary motor sliced and rolled flat. The primary of a LIM is analogous to a stator and usually makes up the windings of the track. Similarly, the secondary of a LIM is analogous to a rotor. During operation, an alternating electric current is supplied to the coils of the primary to change the polarity of the magnetized coils. This change of polarity results in the magnetic field in front of the vehicle pulling it forward and the magnetic field behind the vehicle also pushing it forward. Examples of this concept can be seen in modern day roller coaster design.

The ALDS LIM requirements include launching a 1,500 lb glider at a speed of 500 kts with an acceleration of 30 g's. This results in a required track length of approximately 365 ft. The closest available design is the Electro-Magnetic Aircraft Launch System (EMALS)[11]. EMALS can launch an aircraft mass between 10,000 and 100,000 lbs at speeds between 50 and 200 kts with a maximum acceleration of 5 g's.

The LIM track design was constrained by the required 30-degree launch angle. A sudden 30$^{o}$ turn at the end of a horizontal track creates excessive centripetal and reaction forces on both the vehicle and the ship. As centripetal force varies inversely with the radius of curvature, a curved track design was investigated. A large radius is desirable but the design is constrained by the ships dimensions. The final track design included a horizontal segment of 183 ft, placed along the keel of the ship, and a curved segment of 182 feet (Figure 44). The track, enclosed in a watertight tube, extends10 ft above the main deck to increase curvature without decreasing flight deck visibility.

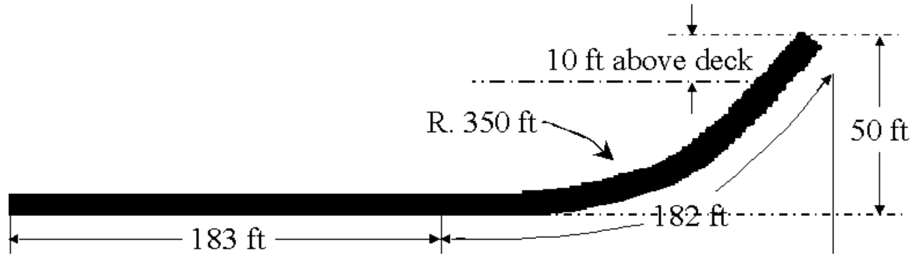



**Figure 44 Linear Induction Motor Track Design**

There are advantages associated with locating the LIM launch tube along the keel of the ship. The first is the minimization of air draft, the distance from a vessel's water line to the upper most point on the vessel. With this LIM configuration, the air draft is based on the height of the deckhouse, eliminating most of the problems related to overhead obstructions such as bridges, cranes, and loading arms. Also, minimal obstruction of visibility from the bridge results. Another advantage of this design is the strong structural support provided by the keel to counteract the large forces generated and absorbing centripetal forces on the curved section. Locating the LIM launch tube within the ship protects the system from weather and keeps the center of gravity of the ship low.

It also allows the weather deck area to remain clear for other uses such as the integration of helicopter pads. One final advantage of this configuration is that locating the LIM launch tube low in the ship allows the cargo handling and assembly rooms to be located high enough in the ship so watertight bulkheads are not necessary.

## 4.8 Ship Scaling

A notional ALDS launch trimaran was developed to explore ship integration issues associated with the system. The length of the ALDS launch trimaran is approximately 600 ft. This approximation is based on length requirements for the LIM launch tube and machinery rooms, both of which are located along the bottom of the ship. Using this 600 ft length estimate and a high-speed trimaran model[12], other ship dimensions were approximated using the appropriate scale factors (Table 6).

| Parameter: | High Speed Trimaran Model | ALDS Launch Trimaran | |
|---|---|---|---|
| Length (LOA) | 23.55 | 600.0 | ft |
| Length (LWL) | 22.82 | 581.4 | ft |
| Center Hull Beam ($B_x$) | 1.37 | 34.9 | ft |
| Total Beam ($TB_x$) | 2.86 | 72.8 | ft |
| Draft FP ($T_{fp}$) | 0.62 | 15.7 | ft |
| Draft AP ($T_{ap}$) | 0.62 | 15.7 | ft |
| Total Displacement | 0.32 | 5,267.8 | short tons |
| Wetted Surface | 44.99 | 29,200.7 | $ft^2$ |
| | | | |
| Side Hull Length (LOA) | 3.71 | 94.5 | ft |
| Side Hull Length (LWL) | 3.71 | 94.5 | ft |
| Side Hull Beam ($B_x$) | 0.23 | 5.9 | ft |
| Side Hull Displacements | 0.01 | 101.0 | short tons |
| Side Hull Wetted Surfaces | 3.98 | 2,584.7 | $ft^2$ |

**Table 6 Ship Scaling Results**

After calculating the scaled parameters, the appropriate parameters were then adjusted to account for the mission of this particular ship. For example, to accommodate the space needed for the ALDS assembly room the side hull length was increased to 120 ft, yielding a cross-deck length of approximately 190 ft. Also, the total displacement according to scaling is 5,267.8 short tons. Based on the required payload and the heavy machinery present on this ship, this displacement could range between 5,000 and 8,000 short tons, increasing the draft and altering the powering requirements.

## 4.9 Ship Layout

Using these overall dimensions as a basis, space was then allotted to the major functions of the ship. As mentioned earlier, the cargo handling room and glider assembly room were placed on the second deck of the ship to avoid the need for watertight bulkheads. Cargo and other materials can be driven into these rooms by means of a retractable ramp on this level located at the stern of the ship. From the assembly room, each assembled ALDS glider will travel down an elevator shaft spanning all three decks of the ship to the level of the LIM. The LIM runs along the centerline of the ship in order to meet damage stability requirements. The extra space remaining along the sides of the launch tube can be used for ship fuel storage. The 200 ft machinery space is located along the keel and spans two decks. This space accounts for both the main machinery rooms (MMR) and auxiliary machinery rooms (AMR). Living quarters space was calculated using a figure of 80 $ft^2$ per person based on the X-Craft design. This figure includes space for staterooms, bathrooms, meeting rooms, mess, etc. for a crew of around 40 people. It is assumed the ship will be manned by a civilian crew and operated by the Military Sealift Command. The crew is composed of 20 personnel to drive the ship and 20 personnel to operate the ALDS assembly and launch process. The wet cargo compartment consists ten % of the fuel and water required by the 6,800 marines on shore and will be packaged in standard water and fuel containers, or have the ability to be packaged in plastic bladders. There is also space for one to three helicopter pads located on the weather deck. All of these spaces were arranged in the most logical fashion to produce the conceptual ship layout (Figure 45).

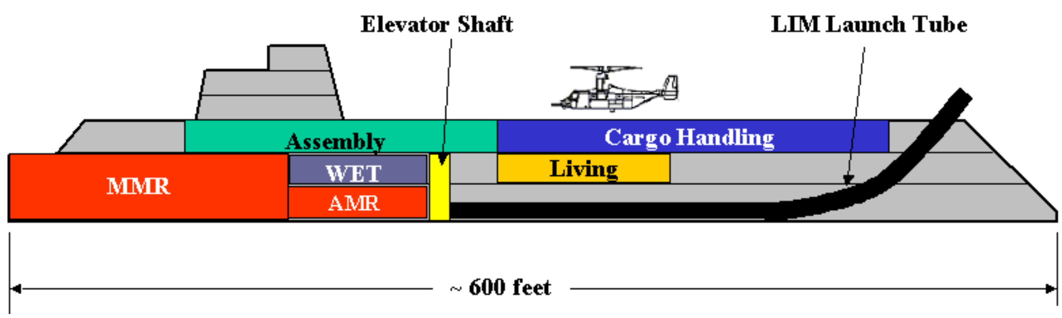



**Figure 45 Conceptual Profile View of ALDS Launch Trimaran**

Table 6 summarizes volume requirements for each of these compartments, idealized as a box. Depth calculations assume that the third and fourth decks are 12 ft tall, while the second deck is 13 ft tall. The remaining 3 ft of the depth estimate accounts for the hull inner bottom and structure.

| Compartment | L(ft) | B(ft) | D(ft) | Area($ft^2$) | Volume($ft^3$) |
|---|---|---|---|---|---|
| Cargo Handling Room | 250 | 35 | 13 | 8750 | 113750 |
| ALDS Assembly Room | 190 | 35-75 | 13 | 12850 | 167050 |
| Elevator | 20 | 15 | 37 | 300 | 11100 |
| LIM/Tube | 380 | 15 | 12 | 5700 | 68400 |
| MMR1 | 80 | 25 | 24 | 2000 | 48000 |
| MMR2 | 80 | 25 | 24 | 2000 | 48000 |
| AMR1 | 40 | 15 | 12 | 600 | 7200 |
| AMR2 | 40 | 15 | 12 | 600 | 7200 |
| Ship Fuel Storage | 250 | 20 | 12 | 5000 | 60000 |
| Diesel Fuel Storage | 20 | 20 | 12 | 400 | 4800 |
| ALDS Fuel Storage | 20 | 17 | 12 | 340 | 4080 |
| ALDS Water Storage | 20 | 17 | 12 | 340 | 4080 |
| V-22 Fuel Storage | 100 | 10 | 24 | 1000 | 24000 |
| Living Quarters | 90 | 35 | 12 | 3150 | 37800 |

**Table 7 Trimaran Compartment Divisions, Area and Volume Requirements**

To further illustrate the ship layout a three-dimensional model was created (Figure 46), which highlights the major features of the ALDS launch trimaran. A complete deck layout is presented in Figure 47.

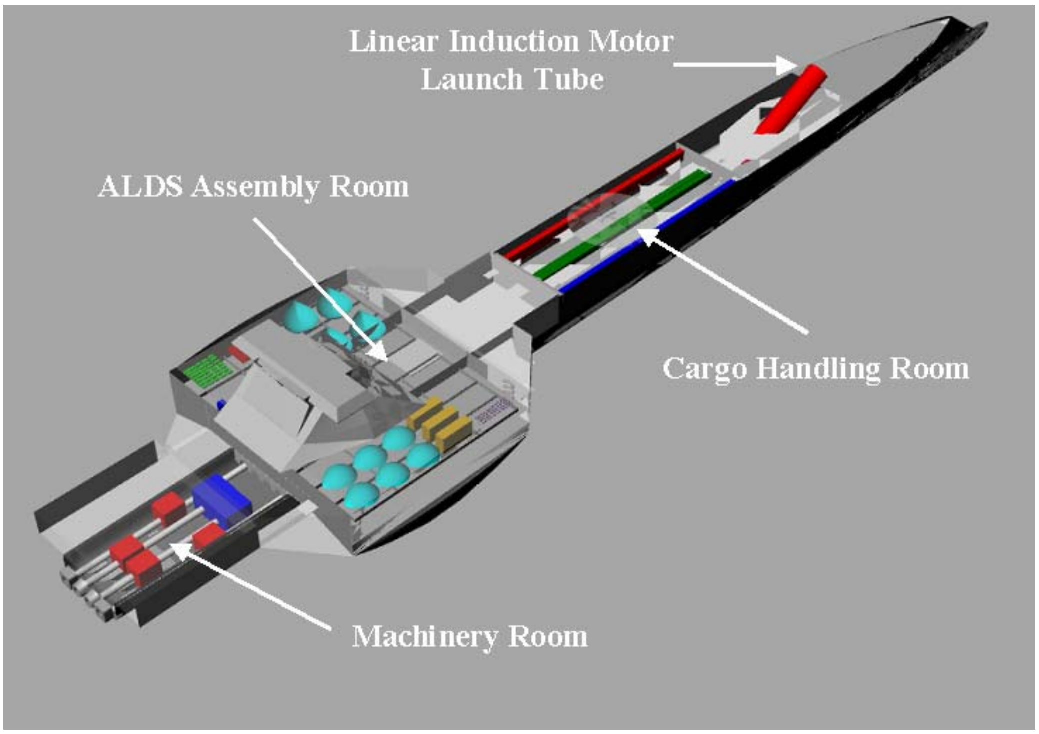



**Figure 46 ALDS Launch Trimaran 3D Model**

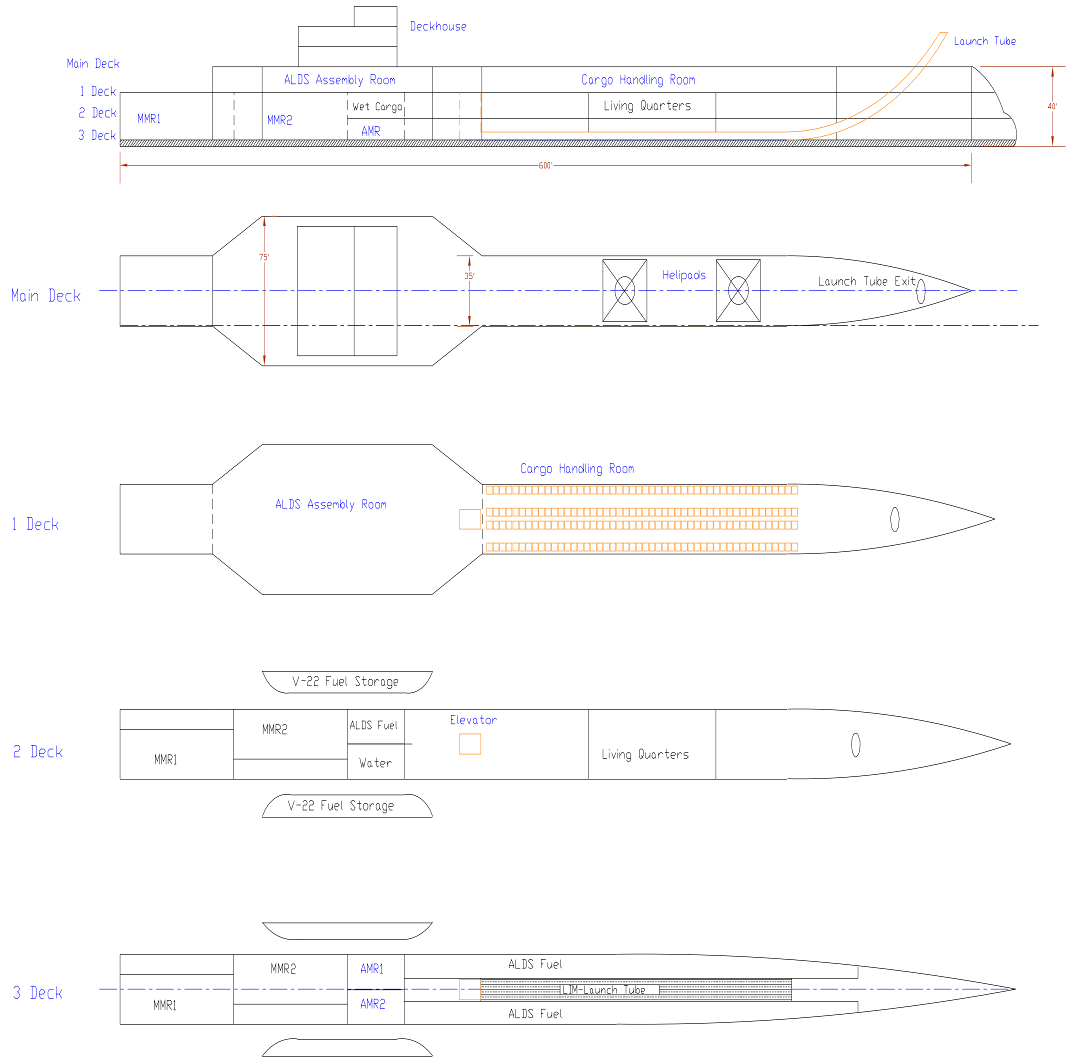



**Figure 47 ALDS Launch Trimaran Deck Layout**

## 4.10 Summary

The objective was to develop a conceptual design for the Advanced Logistics Delivery System launch ship. Using landing force daily re-supply requirements, a four day mission launching 230 gliders per day was identified. It was determined that a trimaran hull was best suited to handle the speed and space requirements of the ALDS mission. ALDS delivers supplies on demand and the necessary cargo handling techniques were identified to meet this requirement. These cargo handling techniques include methods for the transfer of cargo pallets from the sea base to the trimaran as well as automated cargo handling methods onboard the ship. Due to the large volume occupied by pre-manufactured ALDS gliders, methods for manufacturing and assembling ALDS gliders onboard the ship were investigated. Although attractive, significant technology

development is required for such a system to be implemented. A near term solution to this problem was identified in the form of an assembly-only process. This process still features high levels of automation, but also requires further research and development. This problem is not unique to this design as it is currently applies to several other seabasing concepts.

# 5 Linear Induction Motor

A catapult based ALDS system has strong appeal for littoral operations. Modest advances in launcher technology, such as linear induction motors (LIM) similar to those currently under development for use as catapults on aircraft carriers, should allow development of ALDS launcher systems which are sufficiently compact for installation in shallow draft, intra-theater delivery ships displacing a few thousand tons. Furthermore, one of these systems should be capable of providing the launch energy needed while sustaining sufficiently high launch rates to supply maneuvering units on shore. This piece of ships equipment should be more reliable than manned aircraft and require less manpower, maintenance, and fuel.

A notional set of performance and design parameters was needed to initiate development of the ALDS launcher concept. The objective adopted for ALDS is to launch a 1,500 lb vehicle from a ship with sufficient speed to achieve a 50 mile range. Analysis indicated that this required a 500 kt launch speed and a $30^{o}$ launch angle. A cursory examination of ships with the desired capabilities indicated that a launcher length of 350-400 ft was needed to be compatible with overall ship proportions. The launch speed combined with the launcher length limits resulted in a launcher requirement to provide an average acceleration in excess of 30 g's. Other ship design issues considered included ease of structural integration in the ship and impact of launcher height on air draft and visibility. A capability to sustain launches on two minute intervals was selected to give a delivery rate of 15 short tons per hour. These parameters were used to initiate development of the ALDS vehicle, launcher, and ship concepts.

The closest design to the linear induction motor required for ALDS is the Electro-Magnetic Aircraft Launch System[11] (EMALS) planned for installation in future aircraft carriers. EMALS can launch an aircraft weighing between 10,000 lb and 100,000 lb at speeds between 50 kt and 200 kt with a maximum acceleration of 5 g's. While the energy required for ALDS is comparable to that of EMALS, the mass of the launched aircraft is much smaller while launch speed and acceleration are much higher.

The LIM track design was constrained by the requirement that each ALDS glider be launched at an angle of $30^{o}$. A sudden $30^{o}$ turn at the end of a horizontal track creates large forces on both the track and the ship. A large radius of curvature is ideal because increasing the radius of curvature decreases the centrifugal force exerted on the track and the vehicle. However, there is a limit on the radius of curvature of the track based on the depth of the ship. As a compromise, the partially horizontal and partially curved track shown in Figure 48 was selected and placed along the keel of the ship for the baseline launcher concept. The track, which is enclosed in a watertight tube, was also allowed to extend 10 ft above the main deck to increase curvature while minimizing obstruction of visibility from the bridge.

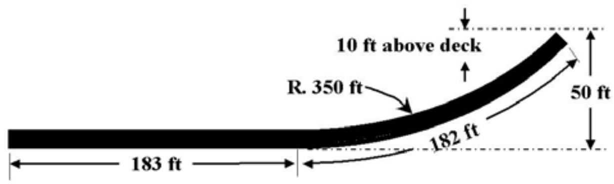



**Figure 48 Initial ALDS Launcher Configuration**

While this baseline configuration was adopted to facilitate development of the ALDS glider design and ship concept, significant development of the launcher configuration and its components is needed. Basic work in this area has been initiated in a study[13] completed by NSWCCD's Machinery Science and Technology Branch. The solution developed is derived from the EMALS system. The extension to ALDS is based on a permanent magnet linear motor incorporating high temperature super-conducting materials in the rotor, stator windings, and electrical wiring. The development of structurally robust, high capability cryo-cooling components was identified as the most critical effort required to field a prototype system in the 10 to 15 year timeframe.

Existing technical capabilities in the areas of energy storage and power electronics were also examined to identify suitable candidates for the major subsystems needed to support the system. While current energy storage technologies were judged adequate for the proposed system, the total size and weight of the system would benefit from additional development. A proposed system derived from EMALS was identified as the most capable power electronics solution since commercial units were deemed inadequate at the power levels required. Additional research to develop more capable switching devices and control algorithms was identified as a prerequisite to achieving the high power and high frequencies needed for the proposed linear motor.

Rough Order of Magnitude estimates of the weight and volume characteristics for the actuator, energy storage devices, and power electronics are shown in Table 8. Volumes are for components only and do not include requirements for access.

| | Actuator | Electronics | Storage | Total |
|---|---|---|---|---|
| **Weight (mt)** | 30 | 26-35 | 20-30 | 76-95 |
| **Volume ($m^3$)** | 20 | 83-146 | 30 | 118-181 |

**Table 8 Rough Order of Magnitude Weight and Volume of LIM Components**

Analysis of the baseline launcher configuration identified a number of issues that have significant impact on the dynamics of the linear motor and the glider as well as the feasibility of the launcher configuration. For example, the discontinuous track curvature at the junction of the straight and curved sections in Figure 48 leads to a large impulsive moment at that point. Also, curvature at the end of the launcher results in the glider being launched with a 2 radians per second spin and a 60 g centripetal load which would present severe challenges to the glider's control system and structural design. Finally, the

requirement to decelerate the launcher bogey after each launch within the assumed track length while maintaining a 500 kt launch speed led to average accelerations greater than 30 g.

A key feature of this technology study was development of several alternative track configurations to address these deficiencies in the initial configuration and analysis of their impact on dynamics of the linear motor. This work identified a set of minimum criteria that formed the basis for development of seven alternative configurations for the ALDS launcher:

- 110 m linear travel for acceleration and braking
- track height less than 32m
- $30^{o}$ slope (first derivative) at end of track
- zero curvature (second derivative) at end of track
- zero jerk (third derivative at end of track
- slope, curvature, and jerk are zero at start of track
- maximum axial acceleration of 30-45 g

Results for these seven alternatives are summarized in Table 9.

| **Configuration** | **Maximum Centripetal Acceleration (g)** | **Launcher Height (m)** | Notes |
|---|---|---|---|
| 1 | 82 | 27 | |
| 2 | 42 | 32 | |
| 3 | 60 | 25 | Recommended for $30^{o}$ launch |
| 4 | 110 | 17 | Inflection point in track |
| 5 | 25 | 20 | Recommended for $20^{o}$ launch |
| 6 | 40 | 16 | |
| 7 | 25 | 16 | $16^{o}$ launch |

**Table 9 ALDS Launcher Alternates**

Track shape and centripetal acceleration for configuration 3 is shown in Figure 49. The launch point is reached after 80 m with the remaining 30 m used for braking the reusable bogey. While some adjustment to the assumed configuration and its components is required, no fatal flaws were found to invalidate the concept of a LIM launcher with ALDS-like performance. Technology requirements to develop an ALDS linear induction motor launcher meeting the performance objectives by 2015 were identified[13].

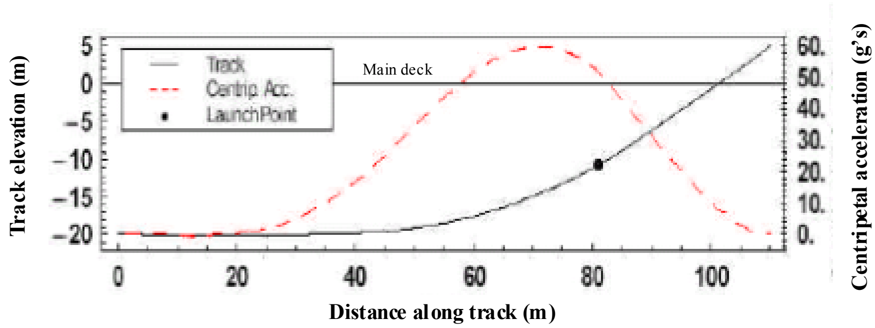



**Figure 49 Track shape and centripetal acceleration for configuration 3**

# 6 System Analysis

## 6.1 Reliability

The main sources of possible ALDS failure are:
Failed launch.
Failure to inflate wings.
Failure of avionics.

The linear induction motor is designed to offer high availability but not necessarily extremely high reliability. If EMALS fails it could result in a loss of an aircraft. If an ALDS glider is lost in the ocean, another body can be launched with little impact to the overall mission. However, if the launcher itself fails and ALDS is unable to launch, mission critical supply of forces ashore will be lost. Linear induction motors generally have a high availability and it is not expected that reliability problems will exist in this area.

If the wings fail to inflate this will result in an ALDS body falling uncontrolled into the ocean. Again, with a relatively inexpensive vehicle, this can be tolerated. However, Vertigo has proven high reliability with their inflation technology.

A failure of the avionics in the climb phase will result in an uncontrolled descent. A failure in the glide phase will result in a stable or unstable descent. The chances of hitting the target would be very slim and the vehicle would probably be lost.

Reliability is a question of acceptable losses. A linear induction motor can be made very reliable but would cost more than accepting a modest failure rate. A similar argument applies to the other failure modes. As ALDS is expendable and relatively inexpensive, the cost of accepting higher losses (as compared to military aircraft) will be much less than creating a system with zero losses.

## 6.2 Effect of Weather

The ALDS ship will have a sea state eight survivability, as it will be deployed from the continental US and will have to travel over the open oceans. However, operating at such a high sea state is unrealistic. The assembly process involves the moving of cargo onboard. A qualitative estimate has been made that the ALDS ship would be fully operational at sea state five.

The ALDS glider can be affected by all weather conditions such as wind, rain, turbulence, thermals and air sinks. Performance results will be very similar to that of sailplanes. With regards to wind, the extreme performance degradation will be experienced with a strong headwind, resulting in reduced range. A strong tail wind will increase the range of ALDS. The ALDS ship cruises along the coast and appropriate points should be chosen to launch, to take best advantage of the wind. Using weather-

monitoring systems on board the ALDS ship, the glider can be programmed to avoid severe weather conditions.

### 6.3 Helicopter Drop Comparison

The ALDS mission is based on resupplying small, dispersed teams. A helicopter therefore would have to go from point-to-point to make relatively small drops. The payload capability of a V-22 is around 20,000 lbs, this equates to twenty ALDS launches. The V-22 would therefore have to maneuver to twenty different locations compared with twenty launches from the ALDS ship direct to the target. The time to deliver would therefore be considerably less with ALDS than one V-22. Additionally, seabasing concepts do not necessarily include the securing of the beach. Therefore, sending a manned, expensive aircraft into a hostile zone is less desirable when compared to the small, inexpensive, unmanned ALDS vehicle. ALDS also offers a lower detectability compared to a helicopter.

### 6.4 Fixed Wing Drop Comparison

Fixed wing airdrops again face the problem of flying a manned aircraft into what is considered to be a hostile environment. However, cargo planes can fly at a much greater altitude to make drops and the Army currently demonstrates techniques of hitting targets within 20 m. Problems arise when trying to integrate the aircraft into a sea base. Fixed wing airdrops require a base for the aircraft to refuel and stock up. With seabasing not necessarily being able to handle military cargo aircraft, this means the aircraft would have to be refueled and loaded from a source outside of the sea base. However, seabasing is attempting to remove the constraint of being dependent upon a land base. Also, there is the logistical problem of keeping the land base supplied (and manned) with the required cargo.

An aircraft can only drop as much payload as it can carry. In the case of a C-130 this is around 42,000 lbs. This equates to 42 ALDS launches. With an estimated 250 drops a day this would require six C-130 sorties. Also, dropping from an aircraft removes the ‘supply on demand’ element of the system, as a large selection of cargo could not be carried on board.

Airdrops usually employ a parafoil design. Current parafoils have moderate to poor glide performance and not enough airspeed to glide into winds. ALDS does not suffer from these problems.

### 6.5 Supplies On Demand

One of the main advantages of ALDS over all other alternatives is the ability to deliver supplies on demand. The whole process could be automated such that the time from request to delivery is about an hour, a significant improvement on current methods.

### 6.6 Requirement of Specialized Ship

ALDS requires a specialized ship, but currently there is no way of providing this capability from sea based assets. ALDS would not sensibly back fit onto large existing

ships such as aircraft carrier as there is no desire to send such high value assets into the littorals. Back fitting onto other ships such as large auxiliaries or current high speed vessels is feasible but will likely lead to significant inefficiencies in ALDS performance and negative impacts in their primary and secondary roles given the space requirements imposed by ALDS logistics.

The ALDS ship has a large amount of unused upper deck space where helicopter pads could be placed enabling a lily pad refueling facility for helicopters operating from the sea base, hence extending their range. The ALDS ship could also act as a support vessel for special forces (launch and recovery). Finally, the ALDS ship frees up air assets for other more important war fighting duties rather than logistics delivery.

# 7 Alternate Delivery Systems

A database of alternate logistic delivery systems was compiled containing parameters such as range and payload Although there are other systems available to deliver logistics to mobile troops, only ALDS was ship based.

## 7.1 Snowgoose

Snowgoose, developed by the MMIST Company consists of a central fuselage and a parafoil canopy (Figure 50). Snowgoose has a maximum combined fuel and cargo capacity of 600 lbs and a range of 160 nm with a 75 lb payload. It has the capability to be launched from the back of a modified HMMWV vehicle, but it sacrifices range and payload with this type of launch. The United States Army is currently procuring the Snowgoose for limited resupply to deployed troops.

**Figure 50 Snowgoose**

## 7.2 Guided Parafoil Delivery System (GPADS)

The Guided Parafoil Delivery System uses a cargo and an avionics package slung underneath a parafoil to deliver its cargo from a high altitude air-drop (Figure 51). It can be deployed from 25,000 ft, with a range of 20 nm and a cargo of up to 1,500 lb. Plans also exist for a version that can carry 10,000 lbs up to 50nm. Both systems are accurate to within 300 ft.

**Figure 51 Guided Parafoil Delivery System**

## 7.3 Semi Rigid Deployable Wing (SRDW)

The Semi Rigid Deployable Wing, is an inflatable wing system that uses a ram-air inflation system to deploy a double sail surface (Figure 52). It has a glide ratio of 10:1 and airspeed of up to 70 kt, while carrying a 600 lb payload. It controls its flight using actuator enabled wing warping over its 30 ft wingspan. The SRDW can be airdropped from up to 25,000 ft with stand off distance of 15 nm.

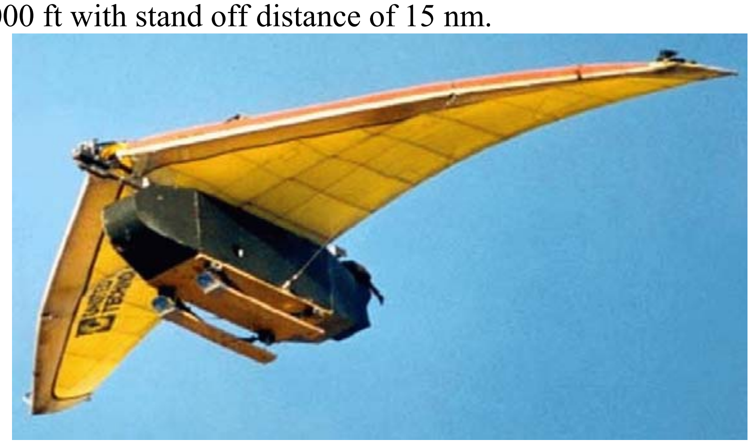


**Figure 52 Semi Rigid Deployable Wing**

## 7.4 Extended Range Aerial Delivery System (ERADS)

The Extended Range Aerial Delivery System is an airdropped inflatable wing system that is designed to deliver up to 12,000 lbs of cargo at a range of up to 40 nm (Figure 53). It relies on an airdrop to achieve its altitude. After release from the transport aircraft, it uses a parachute to deploy an inflatable wing and tail, allowing the system to glide to its target where it executes a normal aircraft landing.

**Figure 53 ERADS**

### 7.5 Comparison of Logistic Delivery Systems

By plotting these alternates onto a range-payload plot (Figure 54), the trade-off between range and payload becomes evident. Although ERADS and GPADS have the ability to carry large payloads when compared to ALDS, their range is quite low. Even without this trade-off, ALDS remains the only ship launched logistics vehicle, providing a great asset to the Navy.

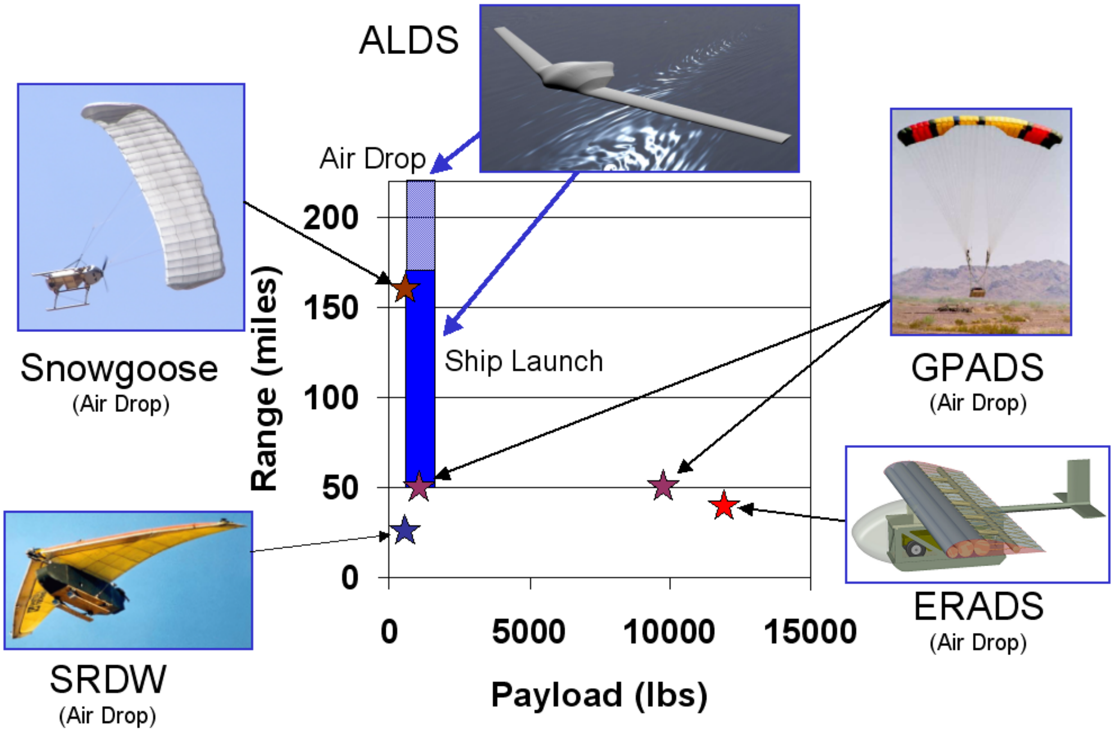



**Figure 54 Range-Payload Plot of Alternate Logistics Delivery Systems**

# 8 Science and Technology Issues (Recommendations for Future Work)

## 8.1 ALDS Glider

- **Inflatable Wing Technology**

The ALDS glider design is at the upper end of current technology, yet is still considered feasible. Vertigo possesses advanced modeling tools for inflatable structures and a study is recommended to assess the ALDS design. The study should also determine at what point the wings should be inflated, along with any associated issues. After an initial study, a small scale prototype could be built to demonstrate the technology. Additional investment to reduced the cost of mass-produced inflatable wings may be required.

- **Preliminary Design**

The centerbody was designed using basic conceptual methods and preliminary studies are now required. Computational Fluid Dynamics (CFD) would allow the centerbody to be aerodynamically optimized to reduce the size, weight and drag, while maintaining the required lift. A detailed structural design also needs to be performed such that the body can withstand all associate loads experienced at launch, cruise and landing. Finite Element Analysis (FEA) would aid in the optimization to reduce structural weight while maintaining integrity.

The ALDS glider is naturally stable and basic stability analysis has been performed. However, flying wings tend to have greater stability issues than tailed aircraft and a detailed analysis is required.

Flying wings, unlike tailed aircraft, do not have a wealth of design tools and experimental data available, due to the small number built. This means the design of a successful flying wing is strongly experimental. There is therefore a desire to build an ALDS glider model. Wind tunnel tests would provide basic aerodynamic characteristics. It is also desired to test the launch by catapulting a working centerbody model. A model of the glide body with moving flaps would prove the concept and aid in the preliminary design.

The above projects could be initiated through university final year student projects.

## 8.2 Launch Ship

- **Cargo Handling**

  Automated cargo handling techniques are required. This is not a problem unique to ALDS and is present with most seabasing concepts. There are already efforts underway to develop onboard cargo handling concepts.

- **Manufacturing Processes**
  A near term onboard assembly process has been identified. The level of automation could be increased and ship stowage space decreased through the development of onboard manufacturing processes. Plastic injection molding is the favored option due to the complexity of shapes that can be manufactured.

- **Slender Trimaran Hull**
  A slender Trimaran hull needs to be designed to aid in the high-speed nature. The linear induction motor also needs to be integrated onboard.

- **Conceptual Design Study**
  Virginia Tech is using the ALDS ship design as a final year student project. The proposal is to develop a more robust ALDS ship design and supporting CONOPS. Ideally the ship design would be developed in parallel with the ALDS glider development. For this study, the objectives are broadly:

  1. Define the necessary ship systems, including propulsion.
  2. Develop a working general arrangement.
  3. Define the onboard materiel needs for ALDS assembly and packaging
  4. Develop a robust cargo handling system, which considers the initial supply from the sea base, onboard handling to support manufacture, and sustainment/re-supply to maintain the operational tempo as defined in the ALDS CONOPS.
  5. Establish the ship demands of providing ‘lily-pad’ support to a wide range of military helicopters and integrating these demands into the design.
  6. Develop a weight and space summary.
  7. Conduct a seakeeping assessment to define operability and the expected area of operations.
  8. Conduct an intact and damage stability assessment

## 8.3 Linear Induction Motor

Technology development requirements to field a prototype ALDS launcher in the 10 to 15 year timeframe have been identified[13] for launch actuators, energy storage systems, power electronics, and track configuration and structures.

- **Launch Actuators**
  A low temperature ($40^{o}$ K) Linear Bulk Superconductive Magnetic Motor technology was selected for ALDS in preference to linear induction or linear

permanent magnet motors because it provides the highest force versus rotor weight, allows much higher magnetic generation, and has a nearly unity power factor capability. Continued research in the extremely high field superconducting magnet technologies with extremely low temperatures is required to reach ALDS goals.

Investment in high power, high g capable cryo-coolers and relater components will be required.

- **Energy Storage Technology**
  While current energy storage technologies are adequate to meet ALDS requirements, further development will improve power density capabilities to reduce the impact of launcher weight and volume on ships.

- **Power Electronics**
  The most critical power electronic needs for ALDS are high power switches and high frequency switching algorithms. Current COTS equipment cannot meet the requirement.

- **Track Configuration and Structures**
  Development of a high rigidity curved track capable of handling high axial and centripetal g forces is needed. Advances in track material science are needed to address insulator ablation during operation. Integrated design studies addressing the integration of the launcher in representative ship concepts are needed to optimize the configuration and performance characteristics of the ALDS launcher.

# 9 Conclusions

ALDS is a shipboard mechanically launched glider capable of providing rapid sustainment of goods and supplies to dispersed military forces maneuvering ashore. Whilst an advanced concept, this report demonstrates that such a system is feasible. A base concept has been developed capable of carrying a payload of 1,000 lbs over a range of 50 miles. With the addition of disposable rockets, the range can be extended to about 160 miles. Use of the same amount of launch energy with heavier payloads can be accommodated, albeit with commensurate range reductions.

ALDS is a very attractive concept to provide on-demand logistics sustainment to forces maneuvering ashore, but investment is required to advance the technological concepts to attain the full potential. The unique feature of the design is the use of large, swept inflatable wings that deploy at the apogee. Such technologies do not yet exist although primitive forms have been demonstrated. Significant advances are also required in LIM technology to support the high launch speeds with a curved launcher.

ALDS has the potential to play a key role in future seabasing missions, bridging a much needed capability gap in sustaining forces ashore. Deploying from a ship means large amounts of cargo are available for frequent, on demand delivery by ALDS.

# 10 Acknowledgements

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